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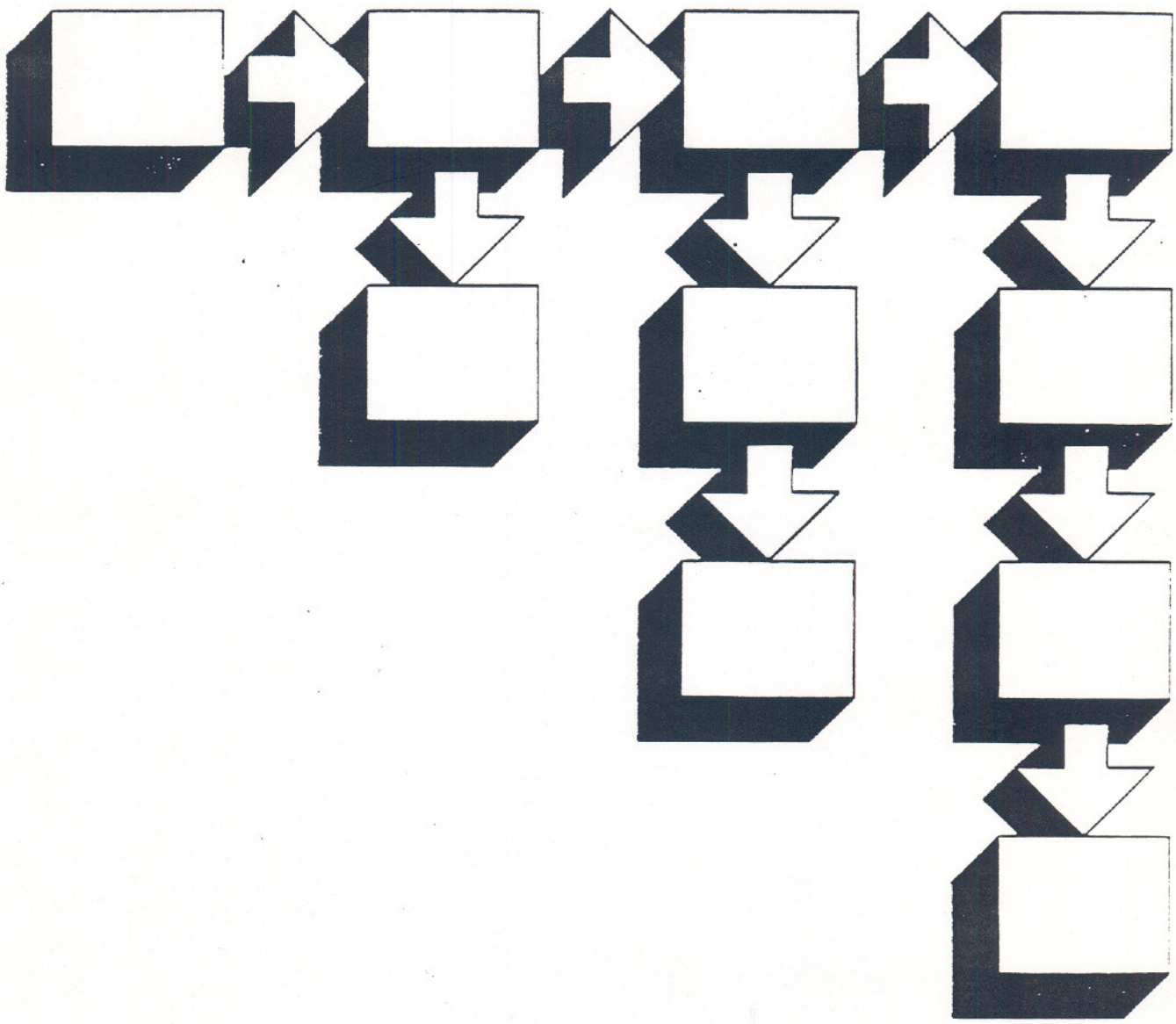
An Automated Fingerprint Identification System



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ABSTRACT

Procedures are described for automatically identifying fingerprints. Machine-read ridge-direction and minutiae data are utilized in registering and enhancing search or file minutiae data. The quality of the data is measured. A procedure is then described for utilizing this minutiae data in determining whether two fingerprint impressions were made by the same finger.

Key Words: computerized-fingerprint-identification; identification; pattern-recognition.

1. INTRODUCTION

The unique identifying data in inked fingerprint impressions on standard fingerprint cards can now be read automatically when the prints are of good quality.[1,2] The data from latent (scene of crime) fingerprints and poor quality inked fingerprints can be read with semiautomatic readers.[3] The first part of this paper describes the automatic procedure for preparing this data so that it can be stored in a file or searched against data that has been previously placed in the file. The second part of the paper describes the automatic procedure whereby a computer can compare search and file data and determine whether or not the represented fingerprints came from the same person.

2. FINGERPRINT DATA

The automatic fingerprint readers at the Federal Bureau of Investigation can deliver both ridge-direction and minute-detail data from each of the ten fingerprint boxes on a fingerprint card.[4,5] Ridge-direction data consists of angles indicating the ridge directions at equally spaced grid points superimposed over the entire print. The reader also determines the X and Y coordinates and the direction, θ, for ridge endings and bifurcations (minutiae). A portion of a fingerprint along with plots of ridge directions and minutiae are shown in Figure 1.* Figure 2 shows how the X and Y coordinates, measured in units of one-tenth millimeter, and the direction θ, measured in degrees, are defined for a minutia. If the areas marked A are ridges, then the minutia is a ridge ending; but if the areas marked B are ridges, the pattern is a bifurcation. Since a ridge ending in one print may appear as a bifurcation in another print from the same finger, no distinction is made between ridge endings and bifurcations in recording data.

Part I: Preparation of Fingerprint Data

1. Registration

Ideally, the core of a fingerprint should be in the center of its appropriate box and the finger should be parallel to the vertical lines of the card when the impression is made. In practice, the print is rarely centered and may be at an angle of more than 20 degrees with the vertical. In order to relieve the matcher of the burden of aligning fingerprint data at match time, registration or centering and aligning is performed on the data before it is placed in the file or searched against a file.

The R92 registration procedure is defined in Flow Charts 1 through 6 and various details will be referred to by the box numbers within these charts. R92 uses the 29 X 29 array of ridge direction data, $\psi_{i,j}$, delivered by the fingerprint reader to find the core or center point (XX, YY). Figure 3 is a plot of the ridge direction array of an ulnar loop. The angles $-90. \leq \psi \leq 90.$ are in degrees and missing angles have the false value 100 for easy recognition by the computer.

[1]Raised figures refer to literature references appearing on page 16.
*Figures and flow charts appear on pages 17 through 44.

The parameters used by R92 are:

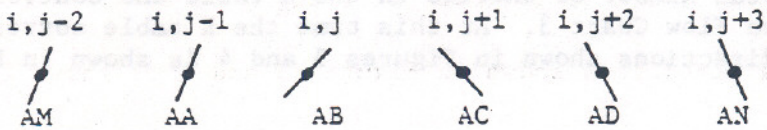
RK 1	RK 2	RK 3	RK 4	RK 5	RK 6	RK 7	RK 8	RK 9	RK 10	RK 11	RK 12
111.	45.	0.	8	73.	76.	176.	3	27	1	25	4

RK 13	RK 14	RK 15	RK 16	RK 17	RK 18	RK 19	RK 20	RK 21	RK 22	RK 23	RK 24
50.	100.	75.	3	9	3	465.	379.	379.	210.	90.	7.

RK 25	RK 26	RK 27	RK 28	RK 29	RK 30	RK 31	RK 32	RK 33	RK 34	RK 35
3	4	3	10	2	76.	45.	30.	180.	0.	2

1.1 Selection of Possible Center Points

Flow Chart 1 seeks all arch-like patterns within the print which might house the core or center point. It begins at the top row, i=RK10=1, and sweeps from left to right as j increases, seeking arch-like patterns that do not include any blank spaces. Boxes 7 - 15 eliminate blank areas where ridge-directions are missing. For each area being examined:



various tests are performed. Box 18 requires that $|AB|+|AC| \leq RK1(=111^{o})$. Box 20 requires that $SAD \geq RK2\ (=45^{o})$. Boxes 21-42 accumulate a confidence score LCR which indicates if the arch is well formed. For example, if box 22 finds that angle AA is greater than 0, box 23 increases the LCR score by 1. If box 42 finds that the total LCR score is less than RK4=8, control returns to boxes 8 and 9 which moves one step to the right for the next set of ridge directions.

If box 42 finds LCR $\geq$ 8, indicating a promising arch, control moves through boxes 43 and 44 to point (L) to Flow Chart 2. Boxes 45 to 58 perform additional tests on the ridge directions above and below point (i,j). If a crossover ( ) is found above in row i-1 or below in row i+1 near column j, then SW>0, and control goes to box 59 where the reference point (i,j) and other information are entered in the K tables. For example:

$$TI_K = i, \quad TJ_K = j, \text{ and}$$

$$TSAD_K = SAD = |\psi_{i,j-1}| + |\psi_{i,j}| + |\psi_{i,j+1}| + |\psi_{i,j+2}|.$$

In Figure 4, showing a portion of the ridge direction data, SAD=246. Control then passes to box 59.01 and on to box 78. During this phase the sum of the absolute values of four consecutive ridge directions from row i+1 is obtained as shown in Figure 4.

$$STX = {}_{i+1,j-3} + {}_{i+1,j-2} + {}_{i+1,j-1} + {}_{i+1,j}$$

Then j is increased by 1 and another STX is computed. This is repeated until there are five different values for STX. The largest of these values is called SXH and the lowest is called SXL. In Figure 4, the largest STX = 335. Hence SXH = 335. The lowest STX gives SXL = 307. SDY = SXH - SAD = 89. These will be entered in the K tables as $TSXH_K$, $TSXL_K$, and $TSDY_K$.

With the above data, box 74 finds that SXL = 307 is greater than RK6 = 76 and control goes to box 75. Here SDY = 89 is found to be larger than RK5 = 73 and box 76 finds SXH = 335 to be larger than RK7 = 176. Thereupon box 77 sets TRY_K = 1 indicating that this area may embrace the core of the fingerprint and that the pattern may be a loop or a whorl.

Control then returns via point (k) to Flow Chart 1 where i and j are advanced so that the entire print is explored for all possible core points which are then added to the K table. After the lowest row of ridge directions, as designated by ILOW and IYLB, has been tested, KM is set to K the total number of entries in the K table and Control goes via point (a) to Flow Chart 3. At this time the K table corresponding to the ridge directions shown in Figures 3 and 4 is shown in Figure 5.

1.2 Analysis of Area Around Center Point

In Flow Chart 3, boxes 84, 85, and 86 seek the last entry in the K table where TRY_K=1. In the above example this occurs when K=8 at the reference point (IYP,JXP)=(12,16). Box 89 then defines two areas around this reference point shown as areas A and B in Figures 3 and 6. Further tests are performed on the ridge-directions in these areas working upward from the bottom of box B. Boxes 94-131 and 144-145 lead to RAS in box 102 which is ten times the mean of the absolute values of the second differences of the angles in area B of Figure 6.

Boxes 132-143 deal with the ridge directions in area A. IC in box 133 is the total number of cases where the absolute values of the angles are greater than RK30(=76°). ITG in box 141 is the total number of times that angles are too large for an arch form in area A. IIF in box 143 counts the number of times that the absolute values of the angles in any row of area A are less than RK24(7°). In other words, this indicates excessive flatness in any row. Boxes 144-154 are again used to accumulate second differences, this time in area A. Boxes 105.1 and 105.2 determine IF, the largest of the IIF values from the three rows in area A. When box 105.21 finds that the analysis of the top row in area A has been completed, control goes via point (n) to Flow Chart 4.

In box 110, RAT is ten times the mean of absolute second differences for area A. This is similar to RAS for area B in Figure 6. The various quantities computed in Flow Chart 3 are renamed and stored in Table K for possible later use. Boxes 114-124 perform various tests on these quantities which may lead to setting SW3=1 in box 125 indicating that this entry in the K table is unsatisfactory as a site for the core. For example, RASK>RK21, where RK21=379, indicates a roughness in the ridge directions like the area around (4,24) in Figure 3 which would be unacceptable for a core area. TIF$\geq$RK26 (4) would indicate that there are too many flat ridge directions in area A. If any of these tests set SW3=1, control upon arriving at box 127 will pass via point (n) to box 86 in Flow Chart 3. Then control will back up in the K table and try the next entry where TRY_K=1.

1.3 Center for a Loop, Whorl, or Tent (CLU=1)

In the example being followed with Figure 6, control arrives at box 127 with SW3=0 and passes through point (C) to box 197 in Flow Chart 5. Since K=KM, box 205 sets CLU=1 indicating the pattern is probably a loop, whorl, or tent and control passes via (h) to Flow Chart 6 where the precise center point (XX,YY) is computed as described in Section 1.6. In box 197, K+2$\leq$KM would indicate that there is some arch pattern below the chosen core area and boxes 198-203 would set out to verify that this is merely an arch pattern under a delta or other harmless anomaly and return to box 205. Failing this, control would pass via point (f) to box 155 in Flow Chart 4 for examination as an arch pattern.

1.4 Center for an Arch (CLU=2)

Before concluding with the computation of (XX,YY) let us return to box 85 in Flow Chart 3. If there were no TRY_K=1 in the K table, control would loop through boxes 86 and 84 till K=0 and then pass via point (f) to box 155 in Flow Chart 4 to locate a center point for an arch pattern. Figure 7 shows the K table for the portion of arch pattern shown in Figure 8. If box 155 finds at least two entries in the K table, boxes 157-163 will start with the reference point (TI_2, TJ_2)=(12,18) and determine that either the previous or following entry in the K table will contain another reference point that is less than two spaces away in the ridge direction matrix. This is true for all of the (TI, TJ) in Figure 8. Consequently, for all entries except K=7 and 8 which are rejected by box 162 for having $TSXL_K$ less than 50°, control moves to boxes 167-170. Here $\Sigma|\phi|$ for each row in Figure 8 is computed and stored as TSA_K in table K shown in Figure 7. For each of these entries that pass boxes 172.1 and 172.2 to point (g), control returns to Flow Chart 3 where the neighboring ridge directions are examined as described in Section 1.2. Note that now SW1=1 so that when control successfully reaches box 126 in Flow Chart 4, control passes through point (d) and on to boxes 174 and 175. Here TRF is set to the largest TSA_K(=392) in the K table and KT=5 notes the entry in the K table of the promising center point for the arch pattern in Figure 8. When the last entry in the K table has been examined,

box 176 sends control via point (p) to Flow Chart 5 for a further examination of the ridge directions under the proposed center point (15, 18) in Figure 8. Boxes 180-194 define an area bounded by the points (16, 16),(16, 21), (24, 16), (24,21) and count the number of times, JC,when $|\psi_{i,j}| \geq 75^{o}$. If JC$\leq$3, box 195 sets CLU=2 and names the center reference point (IYP, JXP)=(TI_{KT}, TJ_{KT}). In the example of Figure 8, (IYP, JXP)=(15, 18). Control then goes via point (h) to Flow Chart 6 where the precise center point (XX,YY) is computed as described in Section 1.6.

1.5 No Definite Center Found (CLU=3)

If boxes 206 and 207 in Flow Chart 5 find CLU>2 and CLX>0 indicating that there was at least one TRY_K=1 in the K table even though none were accepted, then box 209 sets KT=KTX and (JXP, IYP) becomes a "guess" at the center point. (In box 116 in Flow Chart 4 KTX had noted the last entry in the K table where TRY_K=1.) If CLX=0 indicating that there was no TRY_K=1 in the K table, then boxes 208.1-208.5 make one last desperate effort to name a center point by selecting the last entry in the K table where TSDY>36°. If this fails, (XX, YY) is left at (200, 200) and control passes from point (r) to point (e), the end of the program. A few numbers that might be useful for diagnostic purposes are identified.

1.6 Computation of the Center Point (XX, YY)

When control arrives at point (h) in Flow Chart 6, CLU, KT, IYP, JXP have been assigned values. The next task is to obtain a more precise location for the center or core point in rectangular coordinates (XX, YY). This center point marked + for three ridge patterns is shown in Figure 9. The rectangular coordinate system that is used in dealing with minutiae is related to the grid point system of ridge directions as follows:

$$X(j) = .4849(49+24(j-1))$$
$$Y(j) = .4849(725-24(i-1))$$

Boxes 211 and 212 first find the abscissa,

$$XX1 = X+X(j),$$

of a point between $\psi_{i,j}$ and $\chi_{i,j+1}$ as shown in Figure 10. For non-arches, noted by box 213, box 219 uses the ratio

$$\frac{DH1}{DS} = \frac{DSP1}{90}$$

to obtain a measure of the verticalness, DH1, of the ridge directions at (i, j) and (i, j+1). Similarly, boxes 223-226 computer XX2 and DH2 for the next lower row of ridge directions. (The crossover reference point JL=TJL_{KT} was obtained in box 59.01.) Using DH, the mean of DH1 and DH2, box 227 uses the ratio shown in Figure 11 to obtain XX. Box 228 follows, obtaining YY=Y(i)-DS+DH.

For the loop pattern shown in Figures 3, 4, and 6 where (i, j)= (12,16):

$$DSP1=43+67=110$$

$$XX1 = \frac{11.6376x43}{110} + 198.3=202.8$$

Since DSP1 > 90, DH1=DS=11.6376. Since there are no negative ridge directions in row 13, JL=0, XX2=XX1, DH2=11.6376, DH=11.6376, and XX=XX2=XX1=202.8. YY=223.5-11.6376+11.6376=223.5.

With an arch pattern, where CLU=2, control normally goes from box 212 to boxes 215, 215.1, and 216.1. Using the data in Figure 7 which is associated with the arch in Figure 8:

$$(i,j)=(15,18) \qquad DSP1=16+15=31.$$

$$XX=XX1 = \frac{11.6376x16}{31} + 221.6=227.6$$

YY is obtained by a "center of gravity" approach as illustrated in Figure 12:

$$TNUM=177x346+189x392+200x366=208530.$$

$$TDNM=346+392+366=1104$$

$$YY = \frac{208530}{1104} = 188.9$$

The registration concludes in Flow Chart 5 by assembling some additional data for possible future use.

2. (MANGA) Procedure for Improving Minutiae Angles

Due to flaws in the fingerprint image, minutiae direction angles are sometimes in error with respect to neighboring ridge direction angles. For example, see Figure 13. Flow Charts 7 and 8 describe a procedure for correcting these angles by utilizing the angles of the neighboring ridge directions. Box 2 in Flow Chart 7 defines a 2xDSP by 2xDSP square centered about each minutiae. Boxes 3-25 construct a table of the up to K=4 ridge directions (XK_K, YK_K, AK_K) = $(A_{j12}, A_{j22}, A_{j32})$ that surround each minutiae as shown in Figure 14. (Note that $(A_{i11}, A_{i21}, A_{i31}) = (X_i, Y_i, 0_i)$ represents the coordinates and angle of minutia i and $(A_{j12}, A_{j22}, A_{j32})$ represents the coordinates and angle of ridge direction j.) The A_{j32} angles are between -90^o and $+90^o$. The search for ridge directions surrounding a minutia seesaws back and forth across the ridge direction table from j=1 to $j=IMX_2$.

Control now passes via point (b) to Flow Chart 8. In box 28 the distance between the minutiae and each ridge direction, as shown by broken lines in Figure 14, is subtracted from DAG, the diagonal distance of the DS square, and set equal to AT_K. SN is the sum of these weighting factors multiplied by the absolute value of their corresponding angles and AMN is the mean of these products. If AMN is less than 45° as determined by box 33, the neighboring ridge directions are predominately horizontal as in Figure 15, and boxes 34-39 compute the weighted mean angle TP in a straightforward manner. If AMN is greater than 45° indicating predominately vertical ridge directions as in Figure 16, negative angles indicated by box 40 must be converted to positive values before arriving at the weighted mean in box 44. If the absolute value of DA, the difference between TP and the minutia angle, is greater than DAK(=60°), this minutia is deleted from the list of minutiae and control returns via (a) to examine the next minutia. If $|DA| \leq DAK$ the angle value TP replaces the angle in the minutia table and control returns via (a) to consider the next minutia.

3. (NU14) Computation of Rotation Angle $\mathcal{N}$

After the core or center point (XX, YY) of a fingerprint has been determined, the minutiae data will be rotated about this point through some angle $\mathcal{N}$ to a standard orientation for filing or searching. The computation of $\mathcal{N}$ is described in Flow Chart 9 and uses the following parameters:

NUMX	KJC	KJL	KUP	KDN	KCT	KNU1
20.	2	9	3	6	0	20.

Box 2 determines two areas about the reference point (IYP, JXP) shown as area C and D in Figure 3 and as areas A and B in Figure 17 using the parameters KJL, KUP, and KDN. Within this area boxes 9-13 systematically locate pairs of ridge directions $\psi_{i,j}$ and $\psi_{i,jj}$ on the same row and equidistant from the center line as seen in Figure 17. Box 14 computes RN which is half the difference of each of these pairs of angles, and box 15 saves only those RN where $|RN| \leq 30°$. When all of these pairs of angles in areas A and B of Figure 17 have been used, $\mathcal{N}$ the mean value of these RN, is computed in box 22 followed by the sine and cosine in box 24.

4. (TRARO) Translation and Rotation of Minutiae Data

Flow Chart 10 describes the procedure for translating the minutiae data centered at (XX, YY) to the standard center location (200, 200) and at the same time rotating the minutiae pattern through the angle $\mathcal{N}$.

5. (CLIP 3) Elimination of Excess Minutiae

Figure 19 shows the 162 raw minutiae as they came from the fingerprint reader. These correspond to the ridge directions shown in Figure 3. Procedure CLIP 3 retains only those minutiae within the area described

in box 1 of Flow Chart 11. The results of this clipping are shown in Figures 19 and 20; normally PXA=80, PYU=70, PYD=110.

6. (YSORT) Ordering Minutiae Data

The high speed fingerprint matchers M40 and M82 require that both search and file minutiae be arranged in descending order of the Y values. This is accomplished before searching or filing the data by the procedure described in Flow Chart 12.

7. Function DA(TH1, TH2)

The FORTRAN expression DA(TH1, TH2) calls for the procedure described in Flow Chart 13 which computes the difference, DA, between the ridge direction angles TH1 and TH2 making sure that $|DA| \leq 90^{o}$. It is used by the Q6 procedure.

8. (Q6) Measure of Fingerprint Data Quality

The procedure described in Flow Charts 14, 15, and 16 examines the ridge direction data for poor quality in the fingerprint. In Flow Chart 15 boxes 1-19 define a 154 point area in the ridge direction array centered about the reference point (IYP, JXP). Then for each point (i, j) in this area, subroutine QUAL shown in Flow Chart 14 is called upon. In box 7 the Qn differences between the angle at (i, j) and the angle above, to the left and right and below are computed by function DA described in Flow Chart 13. (Ridge direction B_{ij} is the same as ψ_{ij} used in earlier flow charts.) These Qn are first differences comparable to first partial derivatives $\frac{\partial B}{\partial X}$ and $\frac{\partial B}{\partial Y}$. Box 8 obtains QA, the mean of the absolute values of these Qn. In box 9 the second differences QX and QY, comparable to $\frac{\partial^2 B}{\partial X^2}$ and $\frac{\partial^2 B}{\partial Y^2}$, are obtained. The mean of the absolutes of these, Q2A, along with QA are the outputs of this subroutine. MQ=1 indicates that both values could be computed. The results for two ridge configurations about (i, j) are shown in Figure 18. A large value for Q2A indicates a disturbed ridge direction area. Boxes 15 and 21 of Flow Chart 15 obtain the mean values QAM and Q2AM for the entire area of ridge directions defined earlier.

The second part of Q6 in Flow Chart 16 uses the following parameters:

KQ1	QK2	QK3	QK4	QK5	KQ6	KQ7	KQ8	KQ9	KQ10	KQ11
120	17.	19.	20.5	72.	5	95	80	40	20	15

Working with the ridge directions of each fingerprint, it produces a number of demerits, ND, ranging from 0 to 3. If either of a pair of mating fingerprints that are being matched by computer has an ND > 0, the resulting matching score will tend to be low. The larger ND becomes, the poorer will be the matching score. An ND=3 predicts failure to identify the fingerprint and suggests that the minutia

should be reread with a semiautomated reader.

Boxes 24-26.4 accumulate a number of demerits depending on how many of the ridge directions in the 154 areas being examined by QUAL are missing. Boxes 27-32 begin accumulating demerits when Q2AM is greater than 16. If both XX and YY are 200., ND is immediately set to 3 by box 35. Boxes 41-49 count the number of cases, IV, where the absolute values of the ridge directions exceed 72° in the narrow area above the center point defined by box 38. If box 50 finds IV to be five or more, box 51 sets ND=3. Finally, boxes 52-57 give demerits if the total number of minutiae, IMO, is low. In conclusion, boxes 58 and 59 limit the total number of demerits for a fingerprint to three.

9. (PRO) Profusion of Minutia

Subroutine PRO described in Flow Chart 17 constructs a square box centered at each minutia. The box measures 40x40 units when parameter DK=20. The procedure then counts all of the MT minutia in this box. After all of the minutiae in the fingerprint have been thus examined, MD is set equal to the largest MT that was found. Thus, MD is a measure of the maximum minutiae density found in the print.

10. (TIUP) Minutiae Tidy Up

When two minutiae are too close together, one or both minutiae are eliminated. First, boxes 1-3 in Flow Chart 18 clear an array L. Its length is IMO which is equal to the number of minutiae being examined. Boxes 5-22 describe the procedure for detecting two minutiae, i and K, which are less than TK(=10) units apart in X and Y. If this occurs and both minutiae are pointing within TA(=30°) of each other, a note is made in array L by setting L_K=1 in box 17. If the pair of minutiae are pointing in opposite directions, both L_i and L_K are set equal to one in box 20. Boxes 26-31 then eliminate all minutiae identified by a one in array L.

11. (TIUP 1) Another Version of TIUP

TIUP 1 is the same as TIUP except that box 20 contains only $L_{K=1}$. In the case of opposing minutiae, only the second one is eliminated and this appears to produce slightly better matching scores for mating prints.

A comparison of Figures 19 and 20 shows the results of all of the preparation procedures concluding with TIUP 1. For example, minutiae 104 and 105 were too close together in Figure 19. Consequently, minutia 105 was deleted and only 104 remains as minutia 51 in Figure 20. The X, Y, θ data corresponding to Figure 20 can now be placed in the fingerprint file.

This concludes the preparation of minutiae for searching or filing

unless yet-to-be defined procedures are developed for classification and compaction of the minutiae data.

Part II. The M82 Fingerprint Matcher

1. The M40 Matcher

The M82 fingerprint matcher is an extension of the M40 matcher reported in an earlier publication[6]. This extension utilizes a tensor that produces improved matcher scores particularly in cases where the mating prints are distorted. Parts 1 and 2 of the M82 matcher shown in Flow Charts 20 and 21 are essentially the same as the M40 matcher.

Figure 21 shows four search minutiae superimposed on five file minutiae. The file set is displaced, rotated, and stretched with respect to the search set. The X, Y, θ data for these minutiae are shown in Figure 22. As M82 sets out to compare these prints, boxes 1-3 in Flow Chart 20 examine the total number of search and file minutiae and assign the subscript B to the set with the least minutiae (search set) and C to the other set (file set). Boxes 5-18.1 proceed to put a box around each search minutia i as shown in Figure 23. For each file minutia j in this box with $\nabla\theta \leq L\theta$ an entry S is made in the S table shown in Figure 24. The indices i, j for each pair of prints is also entered as IS_S AND JS_S in this S Table. (These values were not saved in the M40 matcher.) The parameters used in this illustration are as follows:

Lθ	LS	Kθ	AKR	KHθ	KHR	KQL	KMX	XYK	ANK	BKR
15	25	0	26	16	26	-9	7	5	15.	5

KRR	PS	BB	CC	DD	EE	KMM
8500	7	20	.2	30	.36	15

2. Computation of R and TS Scores

After the last search minutiae i has been examined, control passes via Ⓓ to Flow Chart 21 where a score R is computed. Boxes 23-23.5 begin by setting all values of table TS to zero. Each entry i in Figure 24 is then compared with each other entry j and the differences TR and Tθ defined in box 25 are computed. Those values of TR which pass the tests of boxes 26-28 are used to compute a score KR-TR in box 28.1 This is added to the TS_i and TS_j at the locations corresponding to the minutiae pairs IS and JS that contributed to this score. For example, using entries i=1 and j=2 as shown in box 25:

$$TR=|1+7|+|6-8|=8+2 = 10$$

$$KR-TR = 26-10 = 16$$

(Note that in box 4 in Flow Chart 20, KR=AKR=26.)

Then in box 26: $TS_1=0+16=16$

$TS_2=0+16=16$

Stated in another way, search minutia 1 in figure 21 sitting on file minutia 1 coupled with search minutia 2 sitting on file minutia 2 produces a score of 16. This is credited to the TS score for each pair in Figure 24.

The same accumulated score called R in box 29 is the R score used to produce the final RS score in the M40 matcher.

3. Ordering and Clipping the S Table

When all combinations of the entries in the S table have been processed control moves via point Ⓒ to Flow Chart 22. Since KSW was set equal to zero in box 4 of Flow Chart 20, control passes to box 34.02 where the switch KSW is set to 1. With mating cards the S table will usually contain more than 100 entries. It is the task of boxes 40-57.1 to arrange the TS values of the S table in descending order and retain the associated IS and JS values. Thus IS, JS, TS become GI, GJ, GT in the J table shown in Figure 25 with the GT now in descending order. This is accomplished by comparing each TS value with each GT. When TS is greater than GT, this GT and the remaining entries in the GT table are pushed down one notch. The TS value is then inserted in the vacated GT space and the process is repeated till all TS values are treated. In practice only KMM=15 entries are retained in the J table. These are normally mating minutiae and their TS contributions to the R score.

4. Computation of the Tensor

Control next moves via Ⓓ to Flow Chart 23 where table J is utilized in computing the four element tensor: COV, SIV, SIW, COW.

The following parameters are used in practical applications:

LΘ	1S	KΘ	AKR	KHΘ	KHR	KQL	KMX	XYK	ANK	BKR
15.47	25.00	.00	8.00	16.00	8.00	-9	7	5.00	15.47	5.

KRR	PS	AA	BB	CC	DD	EE	KMM	FRC
8500.00	7.	0.	20.	.130	40.	.360	15	.0

For the following illustration, some of these will be changed as follows:

AKR	KHR	CC	DD
26.	26.	.20	30.

Box 58.002 assigns the coordinate labels (XXU, YYU) and (XXF, YYF) to the search and file minutiae that produced the highest TS score by using the first entry in the J table in Figure 25. Using the first GI and GJ values and consulting Figure 22 one sees that the search minutia number 2 coordinates are (XXU, YYU)=(181,219) and the file minutia number 2 coordinates are (XXF,YYF)=(188,211). Now, referring to Figure 21, suppose that the search minutiae are superimposed on the

file minutiae so that search minutia 2 sits on top of file minutia 2. This is illustrated in Figure 26. The next ranking pair of minutiae in Figure 25 are search 4 on file 5. Figure 26 shows the X and Y differences XI and YI as they are computed in box 58.006. The displacement of search and file minutiae are shown as XIJ and YIJ. Since $|XI| < |YI|$, control goes to box 58.012 where the specific displacements SYT=-.033 and WXT=.217 are computed. If the conditions of boxes 58.013 and 58.014 are satisfied, these are summed as SY and WX and a count is kept by ISY. The difference between the angles of minutiae search 4 and file 5, TI, is summed as SA and counted as LA in boxes 58.018 and 58.019. (Subroutine ADA is shown in Flow Chart 19.)

Control then increases K1 and moves to box 58.003 where the next pair of minutiae in Figure 25, 3 on 3 is treated. See Figure 27. Since $|XI| > |YI|$ control goes to box 58.008 where SXT=-.186 and WYT=-.100 and these are summed with similar values as SX and WY in box 58.011. The last pass through box 58.003 where (i, j)=(1, 1) produces another trip through box 58.012. The values of the various variables, as control makes three passes through point AA in Flow Chart 23, are shown in Figure 28. When K1 reaches 4, box 58.007 sends control up the left side of the flow chart where the tensor components COV, SIW, COW, SIV and the rotation angle NUU are computed. For example:

$$COV=1 - \frac{-.186}{1} = 1.186.$$

COV is the amount by which one print is stretched in the X direction with respect to the other print per unit of length in the X direction. SIW is the amount by which one print is stretched in the Y direction with respect to the other print per unit of length in the X direction. In other words, COV and SIW deal with distortions in the predominately horizontal area shown in Figure 29. In a similar way COW and SIV deal with the predominately vertical area with respect to the search minutia at (XXU, YYU).

The angle NUU is the mean of the differences between the various pairs of minutiae angles that were used in computing the tensor. Control then moves via (M) to Flow Chart 24. The values of the tensor being illustrated are shown in Figure 30.

5. Transformation of Search Minutiae

The search minutiae will now be moved to new locations as directed by the tensor and some will be eliminated. The new X, Y, θ values will then be used to compute a new S table of DX, DY, Dθ values and control will return to Flow Chart 21 for computation of the final matching score.

Box 61 in Flow Chart 24 computes the XA and YA distance from the reference search minutia at (XXU, YYU) to each of the other search minutiae. If $|XA| \geq |YA|$ box 61.2 computes a new position (X, Y) for this other search minutia, i, utilizing the tensor components COV and SIW. If $|XA| < |YA|$ box 61.3 does the job using COW and SIV. A new angle TH is computed for this minutia by boxes 61.4 - 65. The location

(X, Y) is where the search minutia i would stand in the file minutiae space. Box 66 then constructs a small box about this (X, Y) location as shown in Figure 31. Boxes 67 - 68 then search the appropriate area of the file minutiae table for any minutia j that falls within this box. If the difference between the angles of these prospective mating minutia is less than ANK in box 78, then box 79.1 enters their DX, DY, DΘ values in the new S table. In practical applications this table tends to be limited to true mating minutiae.

To illustrate the above transformation, consider the first search minutiae in Figure 22. Box 61 computes XA=181-168=13 and YA=219-251=-32. Since $|XA|<|YA|$, box 61.3 computes the new location for this search minutia as: X=188+(-32)(.233)-13=167.5 and Y=211+32x1.048=244.5. This places the search minutia almost perfectly on top of the file minutia. The relocated search minutiae coordinates are shown in Figure 32 along with the resulting S table. The superimposed minutiae of Figure 21 after the tensor transofmation now appear as shown in Figure 33. After resetting the parameter KR to a much smaller BKR = 5, control returns via B to Flow Chart 21.

6. Computation of Matcher Score RS

The computer proceeds through Flow Chart 21 obtaining the following values for the DX and DY table shown in Figure 32.

i	j	TR	KR-TR	R
2	1	1	4	4
3	1	1	4	8
	2	0	5	13
4	1	1	4	17
	2	2	3	20
	3	2	3	23

Control then passes via C to Flow Chart 22, and, since KSW now equals one, goes to box 34.03 where R is rounded to IIS for possible future use. The final RS score is computed in box 34.04. SOLD=4 was the value of S from the previous pass through Flow Chart 21 and was saved in box 34.02. IMXB=4 and IMXC=5 are the numbers of minutiae in the search and file sets. S=4 is the present number of entries in the S table. Therefore: $RS = \frac{8500x23x4}{4x4x5} = 9775.$

7. Conclusion

In searching 50 cards against a file of 100 cards all of which are from the ulnar loop section of file, the M82 made a significant improvement in the hit rate when compared with the M40 matcher. The M40 software matcher in the UNIVAC 1108 computer matches a pair of prints in about 2 milliseconds compared with about 150 milliseconds required by the M82 matcher. The M82, like its M40 predecessor, can be built in high-

speed integrated circuit hardware with a significant improvement in speed of performance.

The computer programs used in this work were written and managed by J. F. Rafferty of the National Bureau of Standards. The author is indebted to R. M. Stock of the Federal Bureau of Investigation for advice and assistance. The work was financially supported by the FBI.

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2. Banner, C. S., and Stock, R. M., "FINDER, The FBI's Approach to Automatic Fingerprint Identification, " Proceedings of a Conference on the Science of Fingerprints, Home Office, London, England, 1974.

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4. Banner, C. S., and Stock, R. M., "The FBI's Approach to Automatic Fingerprint Identification, Part I," FBI Law Enforcement Bulletin, Vol. 44, No. 1 (Jan. 1975).

5. Banner, C. S., and Stock, R. M., "The FBI's Approach to Automatic Fingerprint Identification, Part II," FBI Law Enforcement Bulletin, Vol. 44, No. 2 (Feb. 1975).

6. Wegstein, J. H., The M40 Fingerprint Matcher, National Bureau of Standards Technical Note 878, U. S. Government Printing Office, Washington, D. C., 1972.

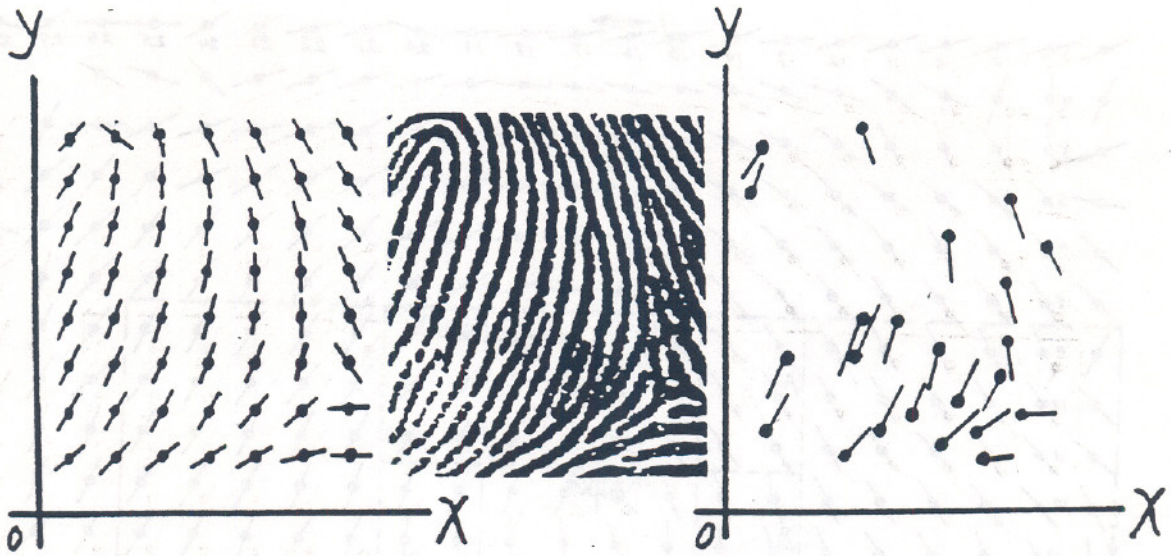


Figure 1. Ridge Directions, Pattern, and Minutiae for a Portion of a Fingerprint

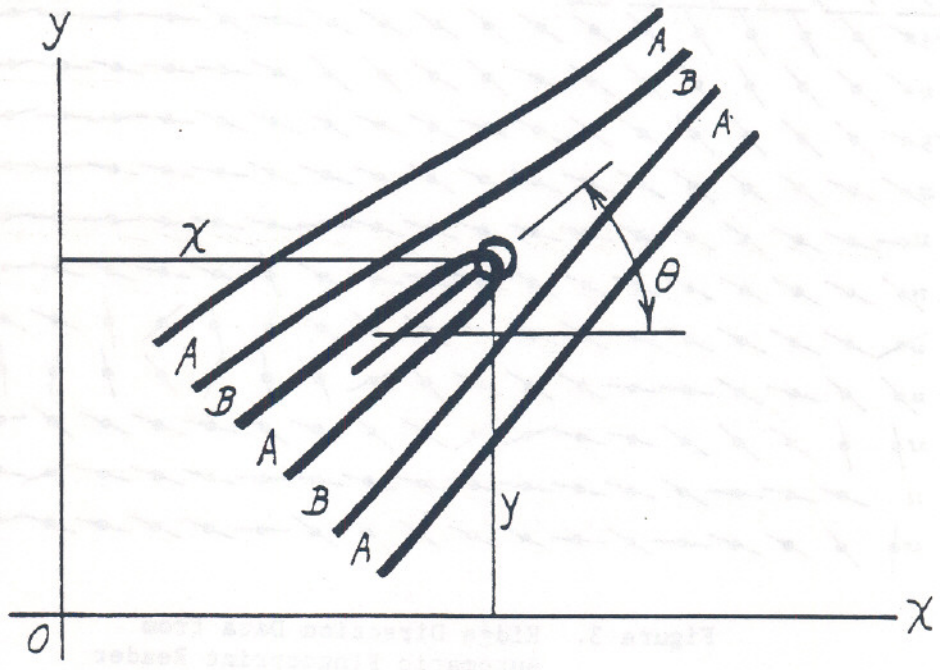


Figure 2. Definition of Minutiae Data (X, Y, θ)

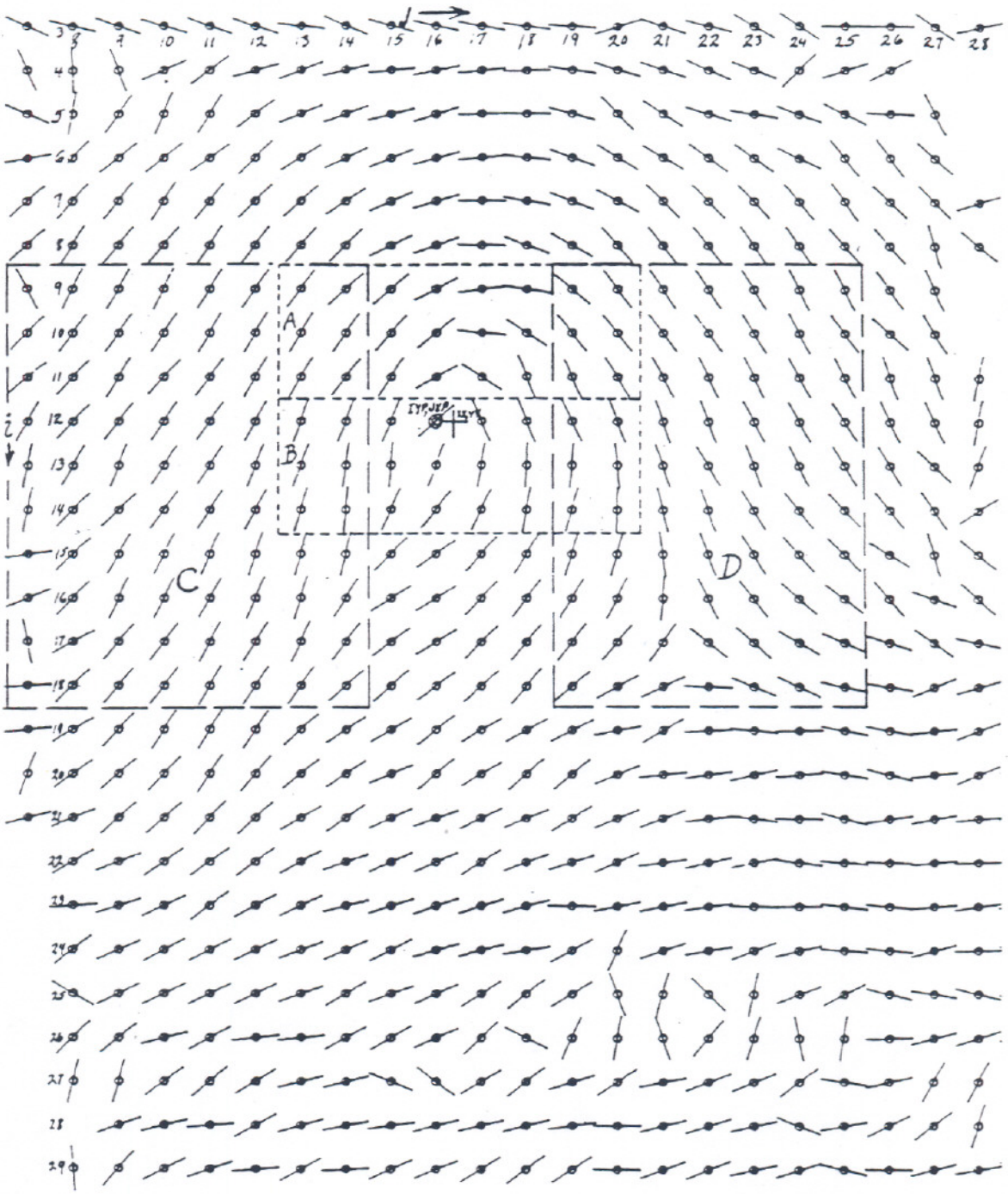


Figure 3. Ridge Direction Data from Automatic Fingerprint Reader

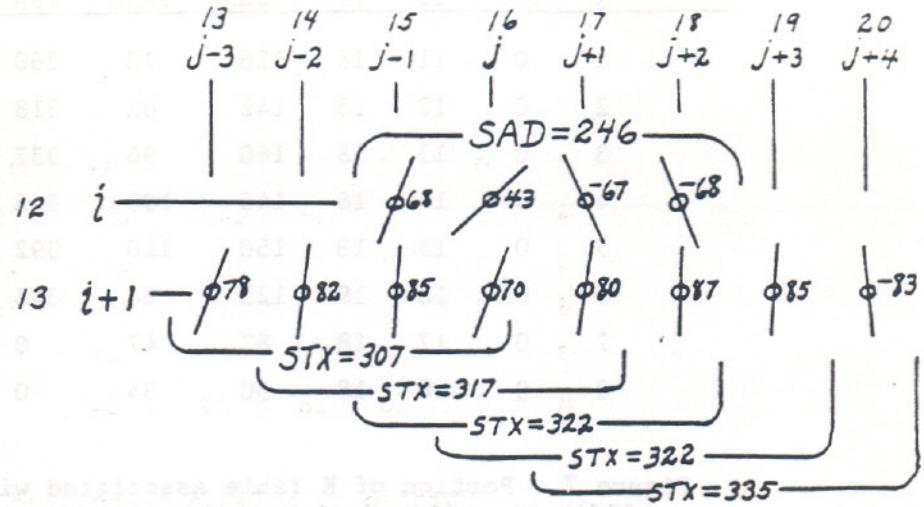


Figure 4. Locating Core Area

K	TRY	TI	TJ	TSBC	TSAD	TLCS	TSDY	TSXH	TSXL	TSW
1	0	5	18	17	67	9	57	123	48	2
2	0	6	17	12	48	10	62	110	50	2
3	0	7	17	10	50	10	107	157	70	2
4	0	8	16	22	70	10	98	168	88	2
5	1	9	17	18	88	10	108	197	132	2
6	1	10	16	47	132	10	98	230	177	2
7	1	11	16	65	192	8	78	270	243	2
8	1	12	16	110	246	8	89	335	307	1

Figure 5. Contents of Table K Upon Arrival at Point a in Flow Chart 1

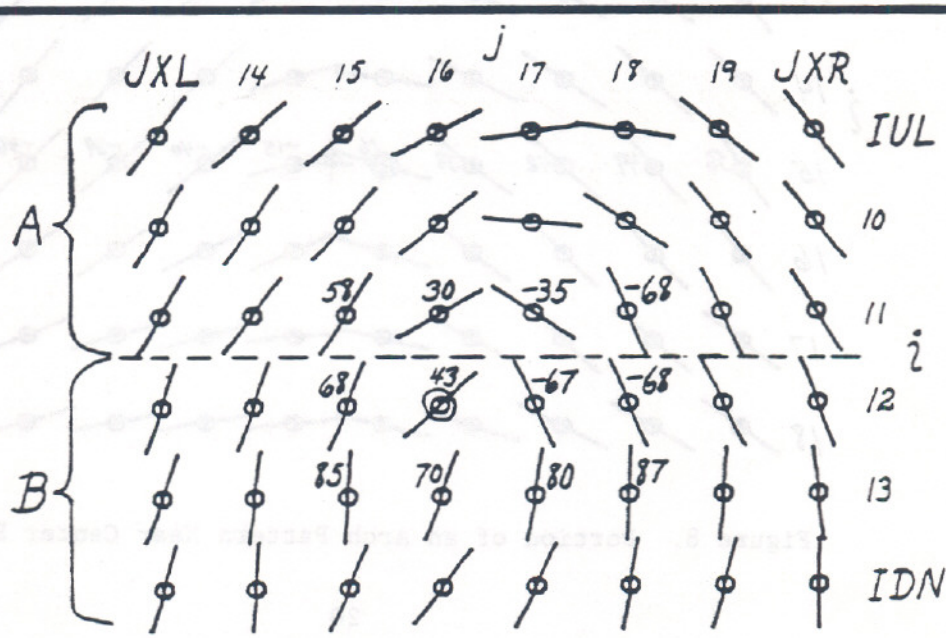


Figure 6. Analysis of Core Area

K	TRY	TI	TJ	TSXH	TXSL	TSA
1	0	11	18	126	73	260
2	0	12	18	142	81	318
3	0	13	18	160	96	337
4	0	14	18	145	109	366
5	0	15	18	150	110	392
6	0	16	18	125	66	346
7	0	17	18	87	47	0
8	0	18	18	50	34	0

Figure 7. Portion of K Table Associated with Arch Pattern in Figure 8

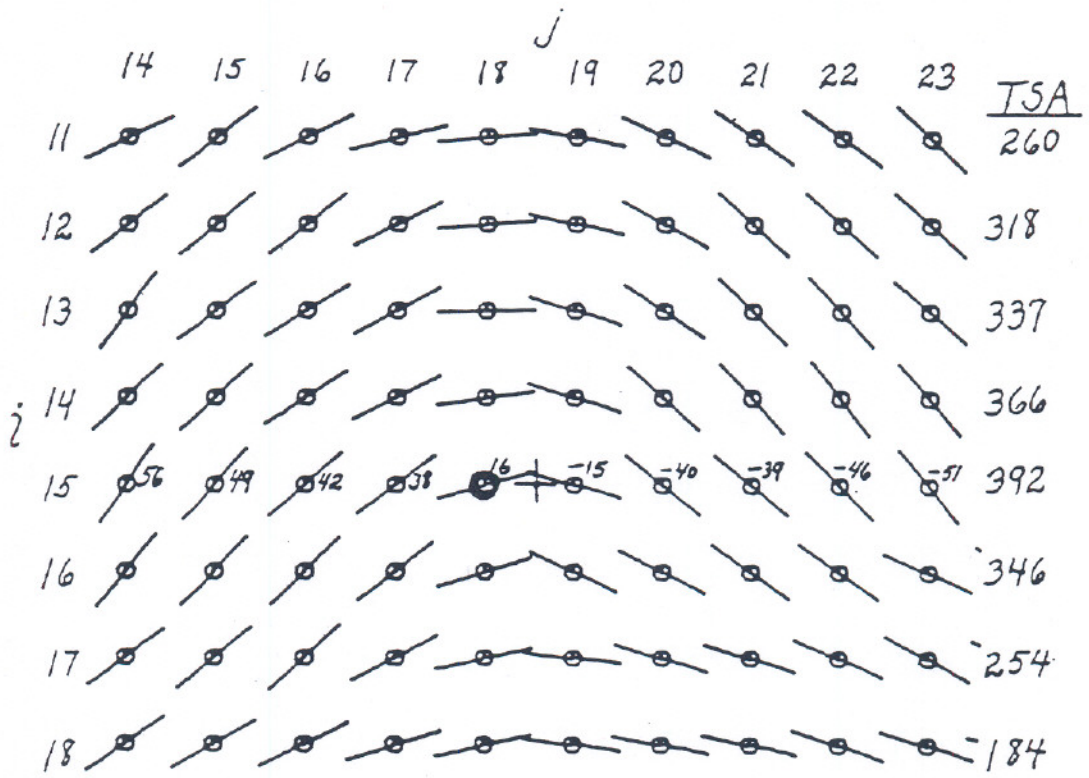


Figure 8. Portion of an Arch Pattern Near Center Point "+"

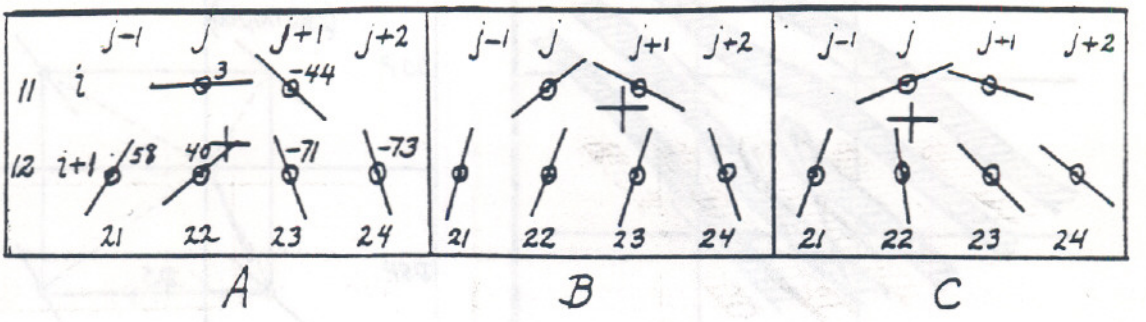
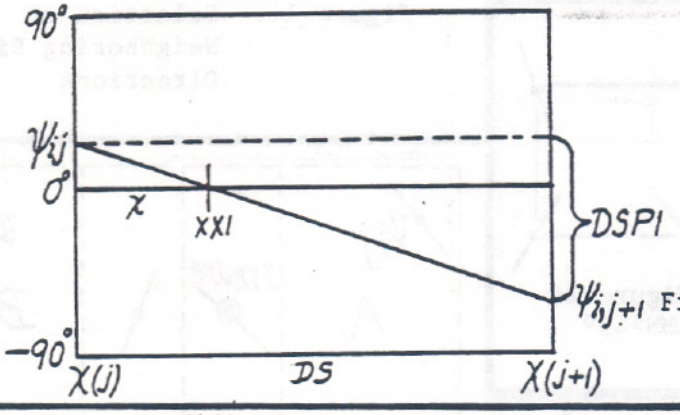


Figure 9. Core Location (XX, YY) Marked "+" for Three Ridge Patterns



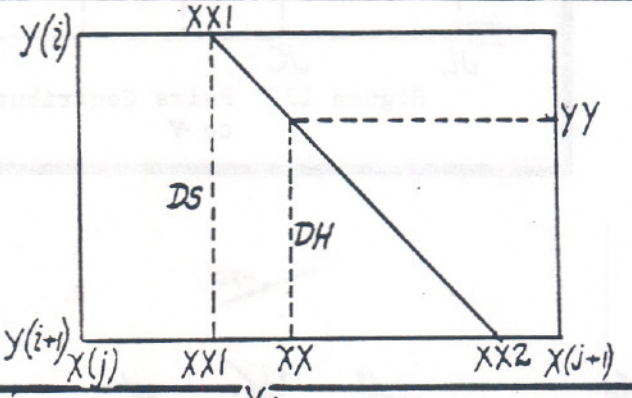
$$DSPI = \psi_{i,j} - \psi_{i,j+1}$$

$$\frac{\chi}{DS} = \frac{\psi_{i,j}}{DSPI}$$

$$\chi = \frac{DS \times \psi_{i,j}}{DSPI}$$

$$XX1 = \chi + X(j)$$

Figure 10. Computation of XX1 for Loops, Whorls, and Arches



$$\frac{XX - XX2}{XX1 - XX2} = \frac{DH}{DS}$$

$$XX = \frac{DH\,(XX1 - XX2)}{DS} + XX2$$

$$YY = Y(i) - DS + DH$$

Figure 11. Computation of XX and YY for Loops and Whorls

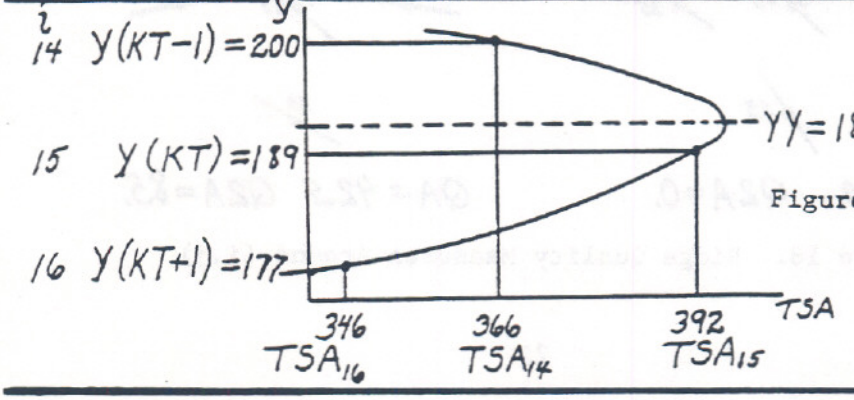


Figure 12. Computation of YY for Arches

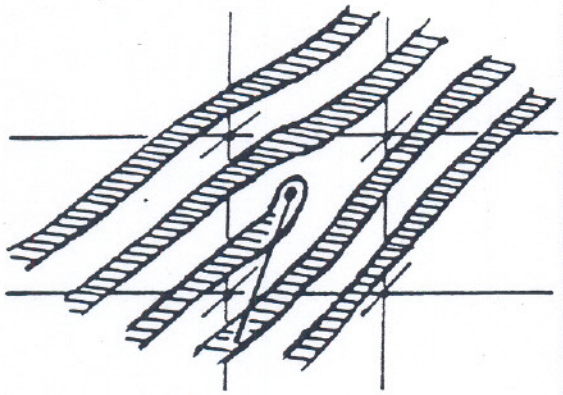


Figure 13. Flaw in Minutia Direction Angle

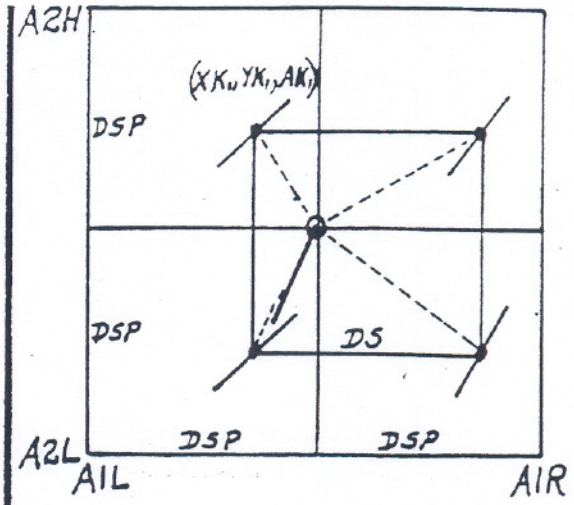


Figure 14. Selection of Neighboring Ridge Directions

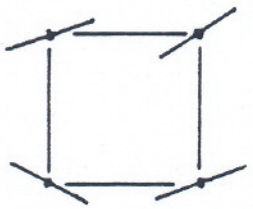


Figure 15
AMN≤45°

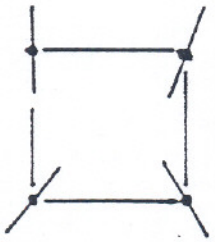


Figure 16
AMN>45°

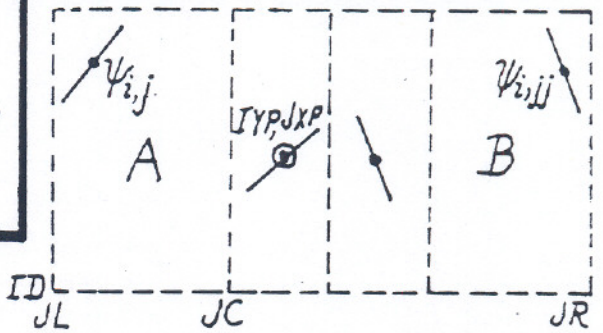


Figure 17. Pairs Contributing to N

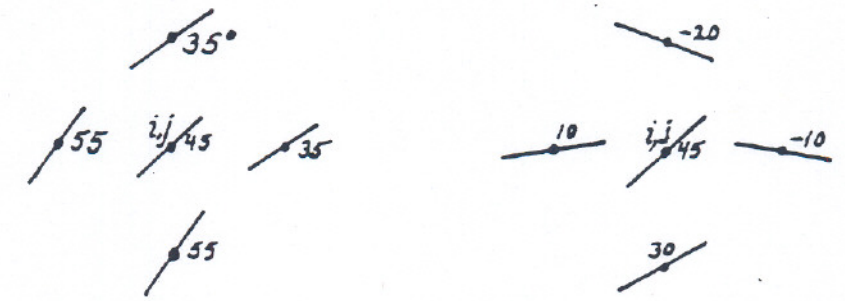


Figure 18. Ridge Quality Measures Around (i,j)

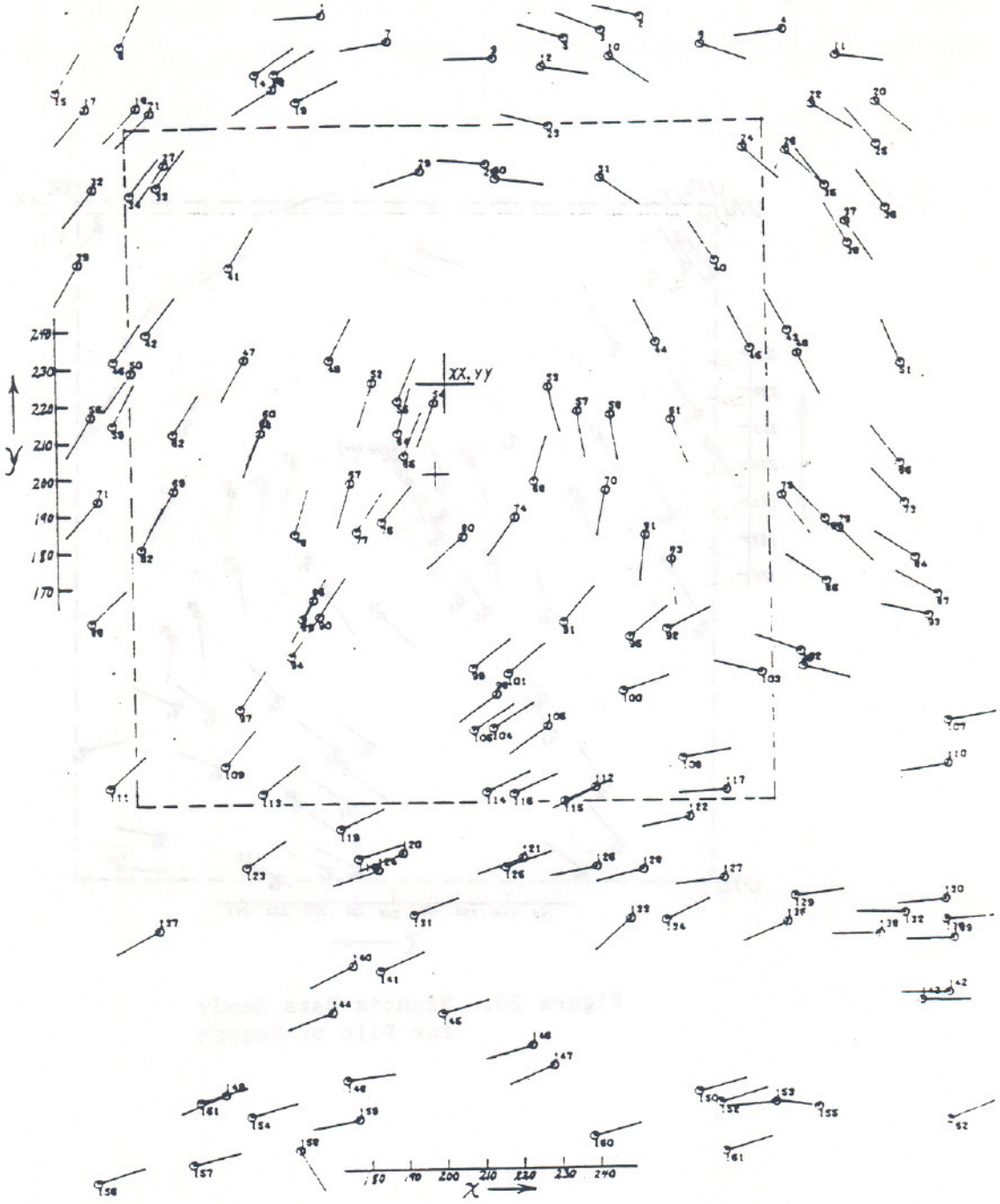


Figure 19. Minutia Data Read by Automatic Fingerprint Reader

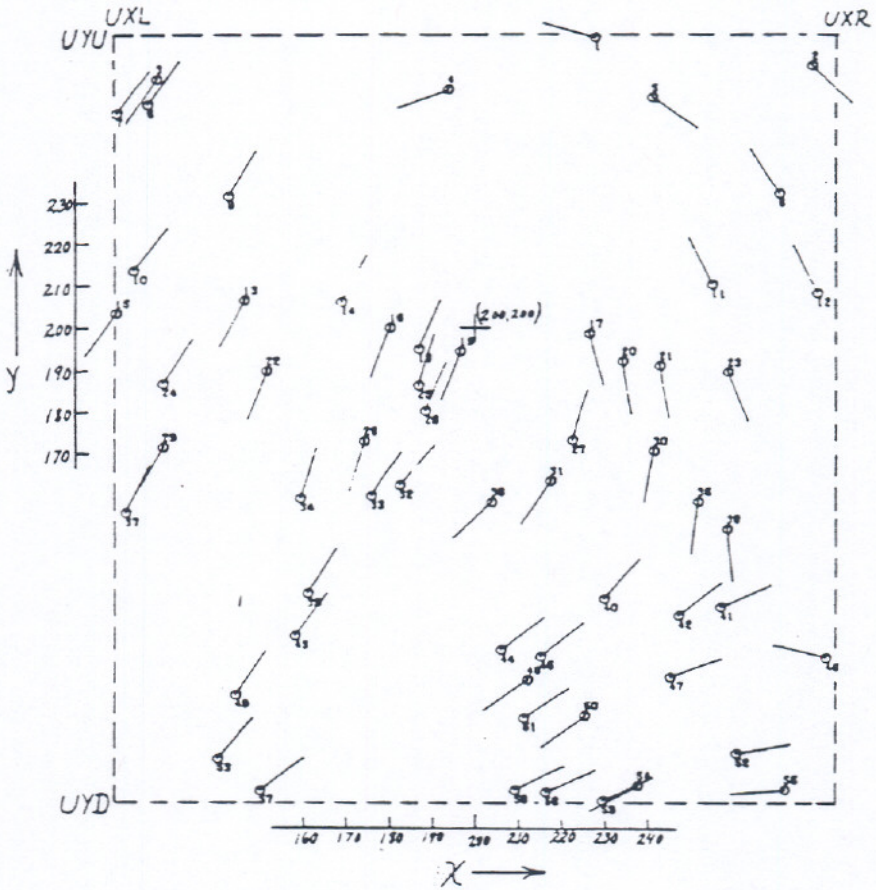


Figure 20. Minutia Data Ready for File or Search

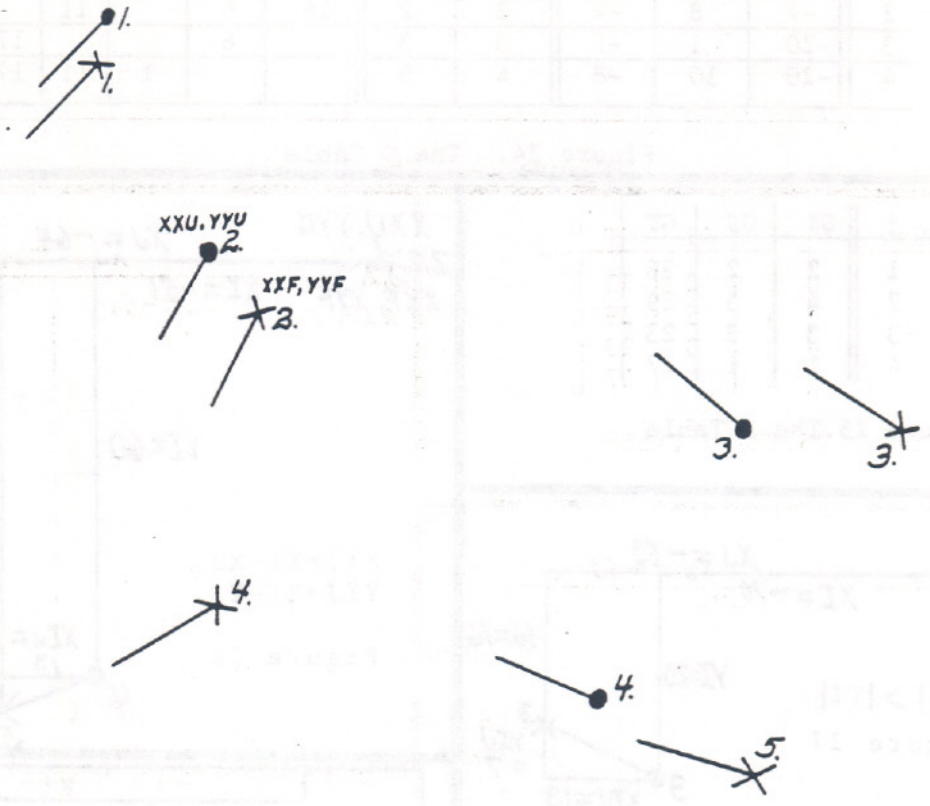


Figure 21. Search Minutiae ● Superimposed on File Minutiae X

i	X Ai1B	Y Ai2B	θ Ai3B
1	168	251	45
2	181	219	60
3	251	196	320
4	232	159	335

Search Minutiae

Figure 22

j	X Aj1C	Y Aj2C	θ Aj3C
1	167	245	47
2	188	211	64
3	271	195	327
4	182	172	30
5	252	149	343

File Minutiae

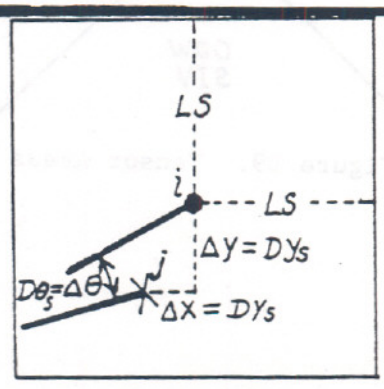


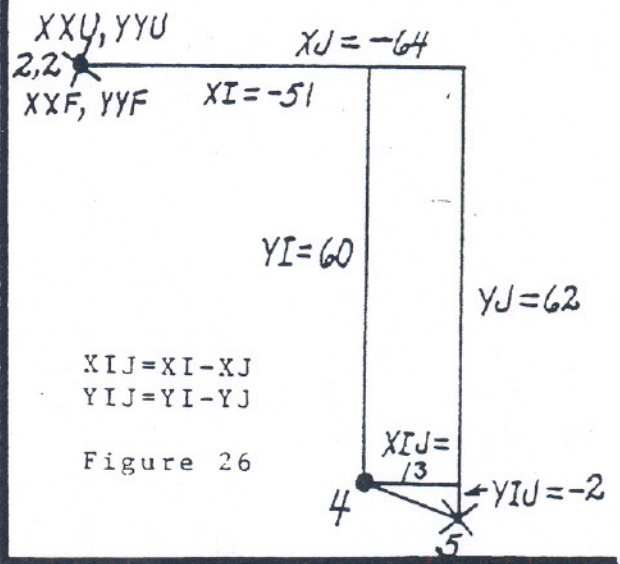
Figure 23. Definition of DX, DY, Dθ

m,i,j,s	DX	DY	DΘ	IS	JS	Contribution					TS	
1	1	6	-2	1	1	16		1			17	
2	-7	8	-4	2	2	16	6		11		33	
3	-20	1	-7	3	3		6			17	23	
4	-20	10	-8	4	5			1	11	17	29	

Figure 24. The S Table

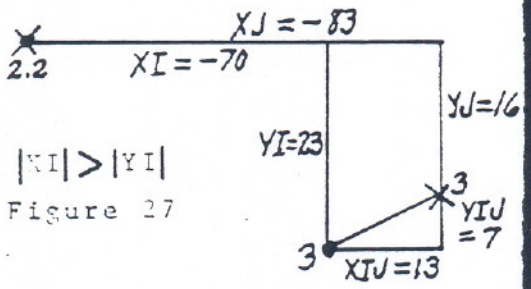
K1, j	GI	GJ	GT
1	2	2	33
2	4	5	29
3	3	3	23
4	1	1	17

Figure 25.The J Table



XIJ=XI-XJ
YIJ=YI-YJ

Figure 26



|XI| > |YI|

Figure 27

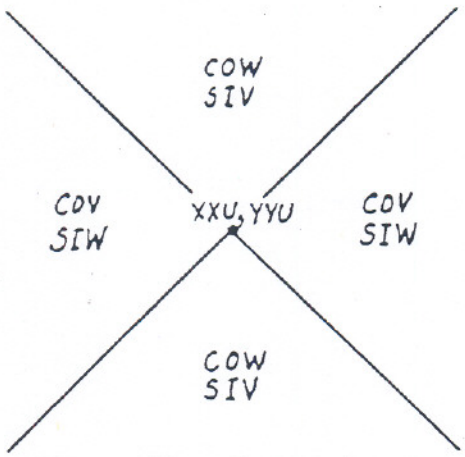


Figure 29. Tensor Areas

	K1		
	2	3	4
i	4	3	1
j	5	3	1
XI	-51	-70	13
YI	60	23	-32
XJ	-64	-83	21
YJ	62	16	-34
XIJ	13	13	-8
YIJ	-2	7	2
SYT	-.033		-.063
WXT	.217		.250
SY	-.033		-.096
WX	.217		.467
ISY	1		2
SXT		-.186	
WYT		-.100	
SX	0	-.186	-.186
WY	0	-.100	-.100
ISX	0	1	1
TI	-8	-7	-2
SA	-8	-15	-17
LA	1	2	3

Figure 28. Tensor Development

COV	SIW	COW	SIV
1.186	-0.100	1.048	0.233

Figure 30. The Values of the Tensor

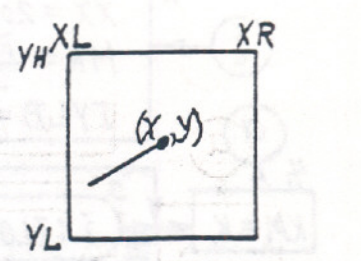


Figure 31. File Space

i	j	XA	YA	X	Y	TH	S	DX	DY	DΘ
1	1	13	-32	168	245	51	1	1	0	4
2	2	0	0	188	211	66	2	0	0	2
3	3	-70	23	271	195	326	3	0	0	-1
4	5	-51	60	253	148	341	4	1	-1	-2

Figure 32. Relocated Search Minutia and S Table

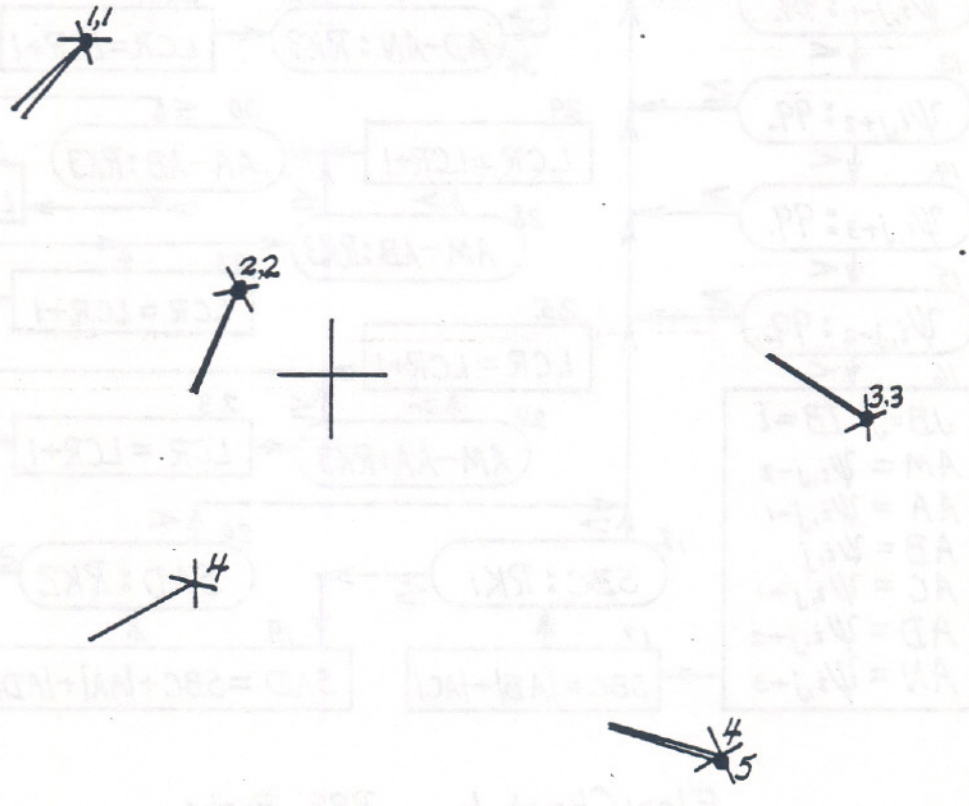
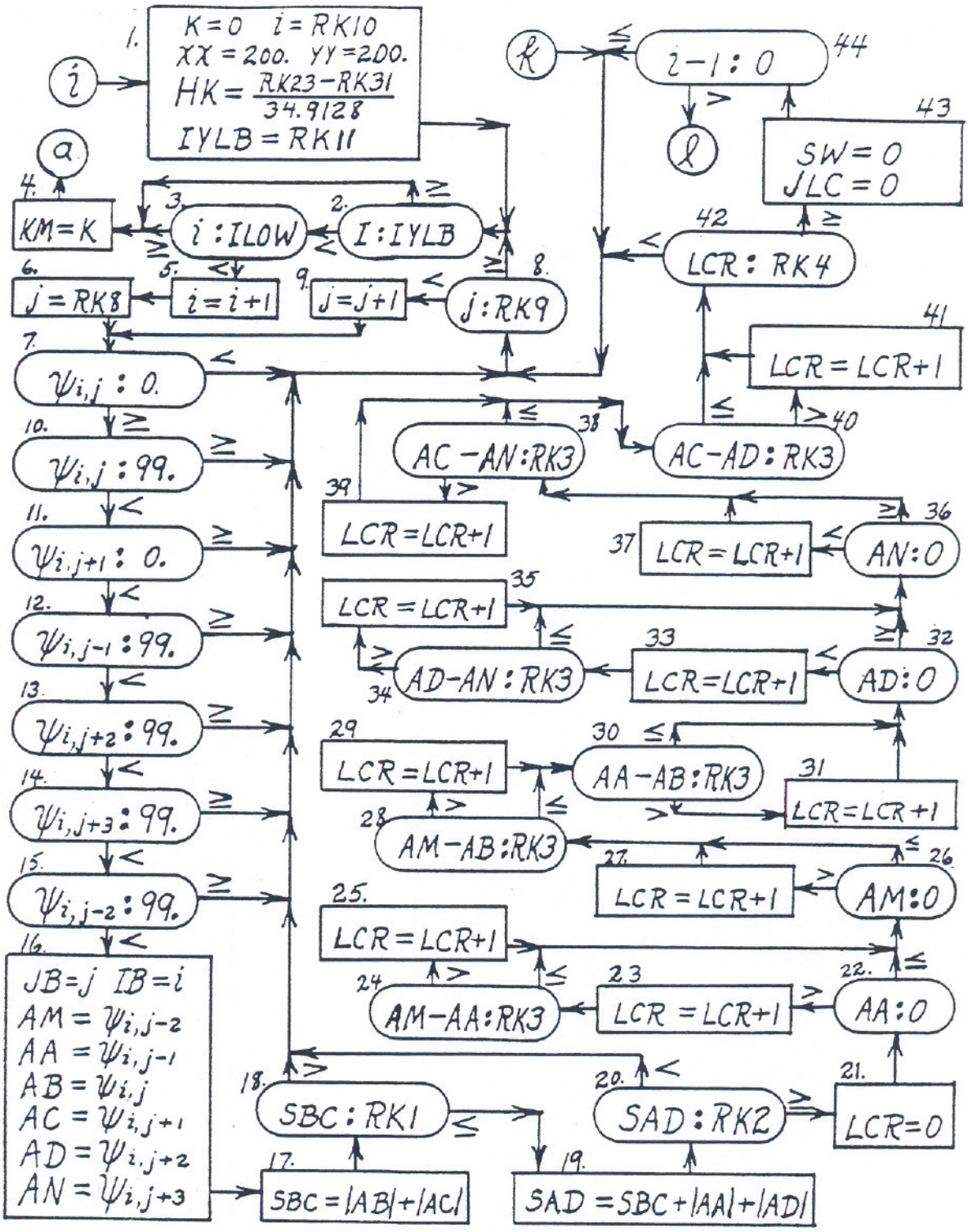
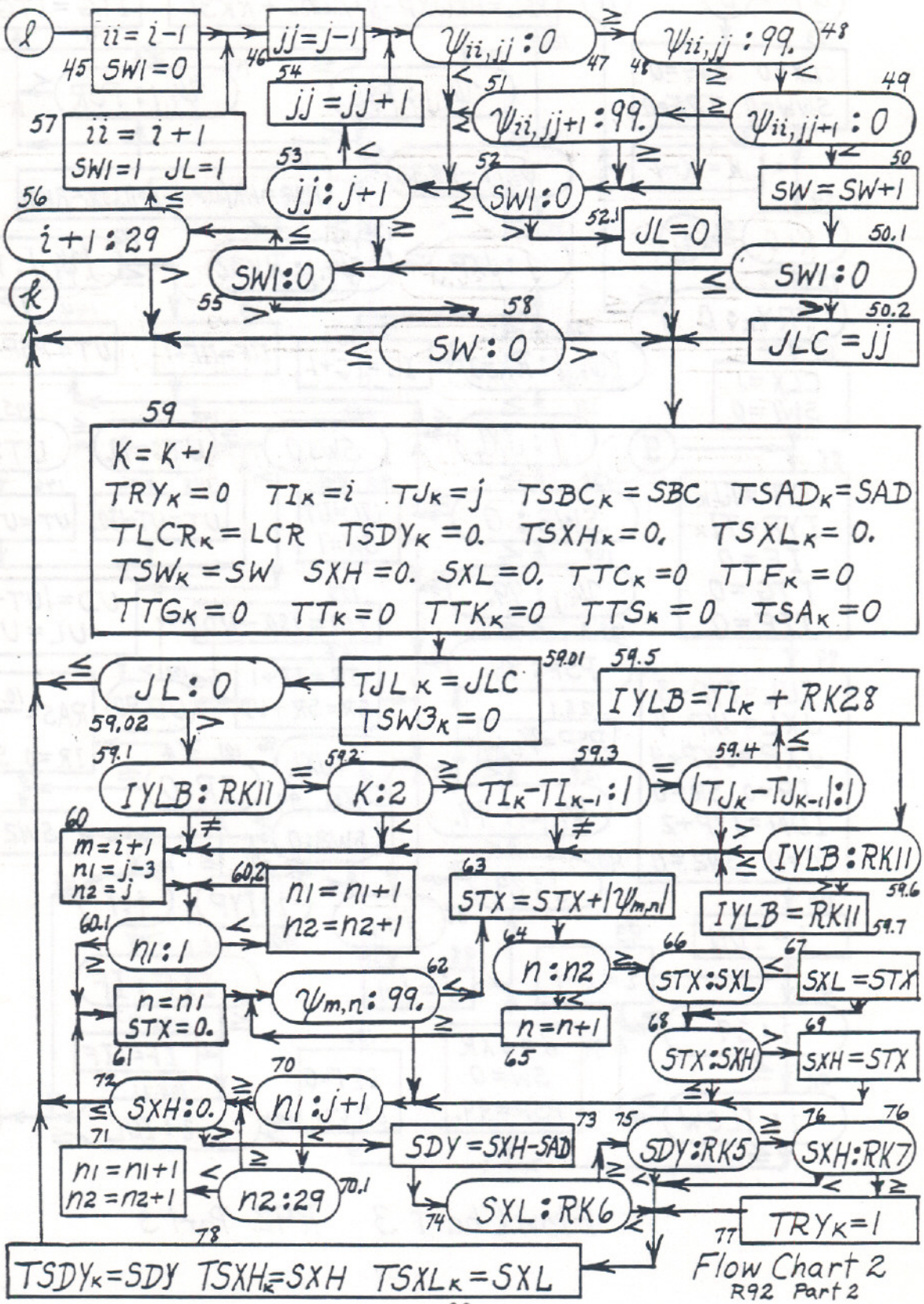


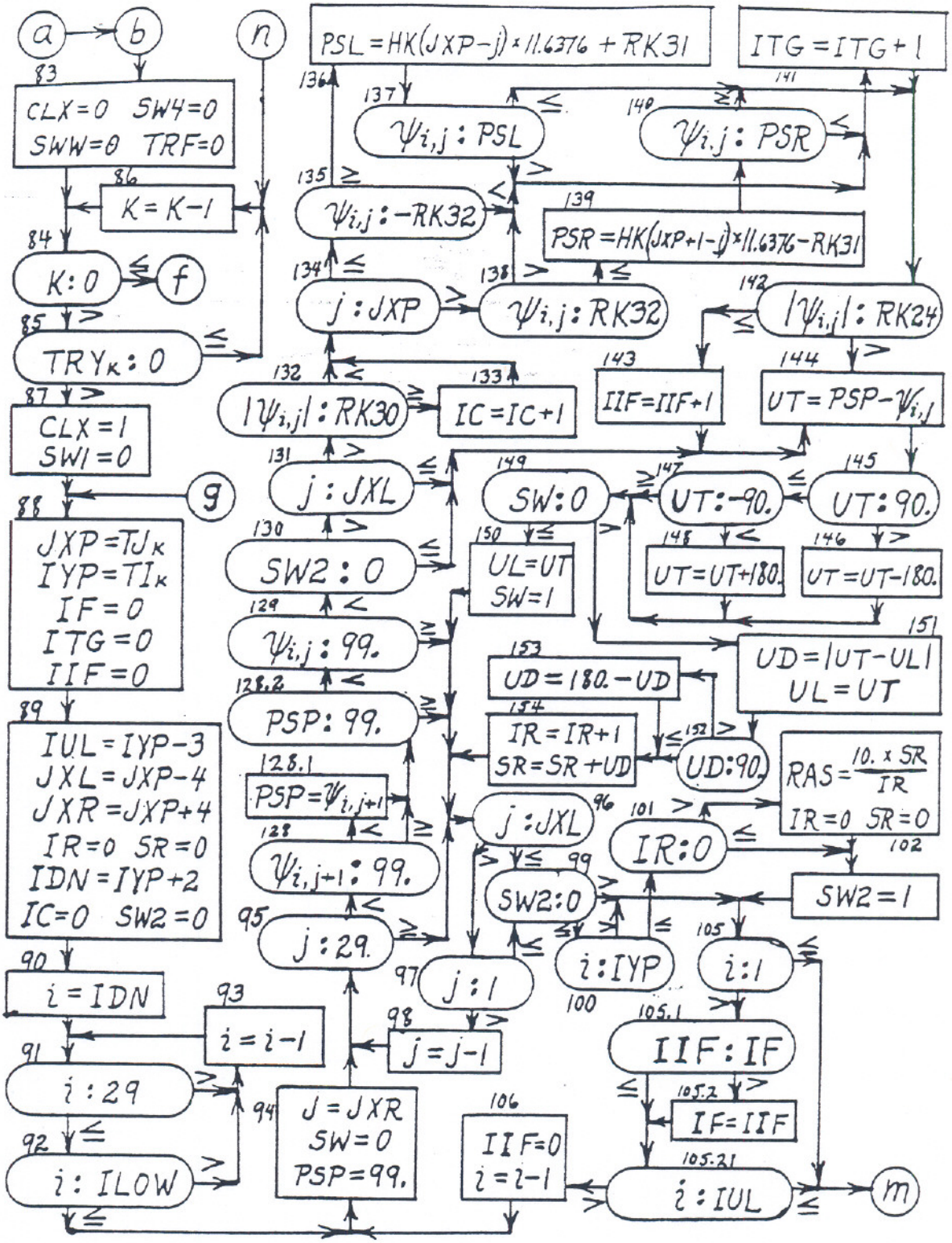
Figure 33. Tensored Search Minutiae Superimposed on File Minutiae



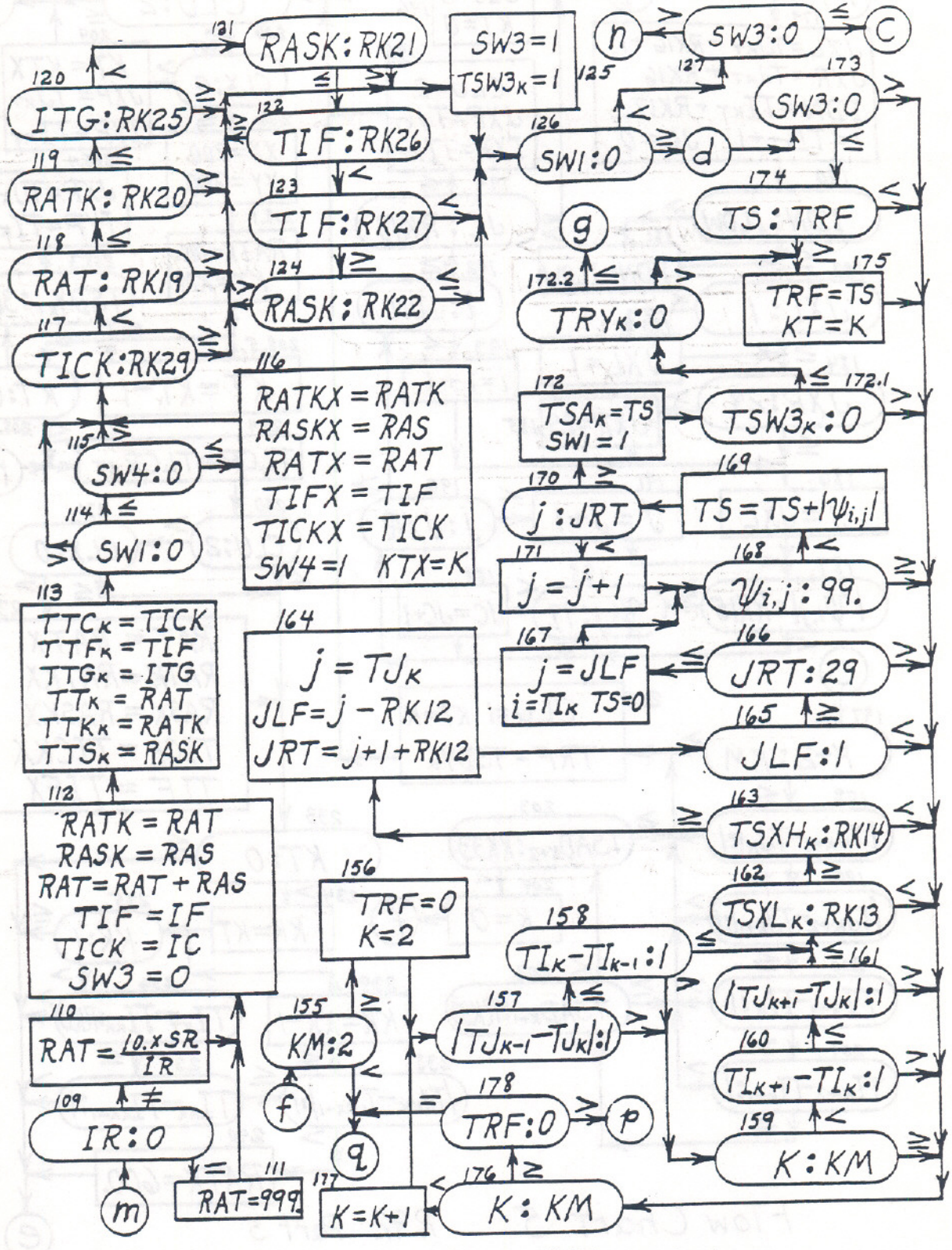
Flow Chart 1 R92 Part 1



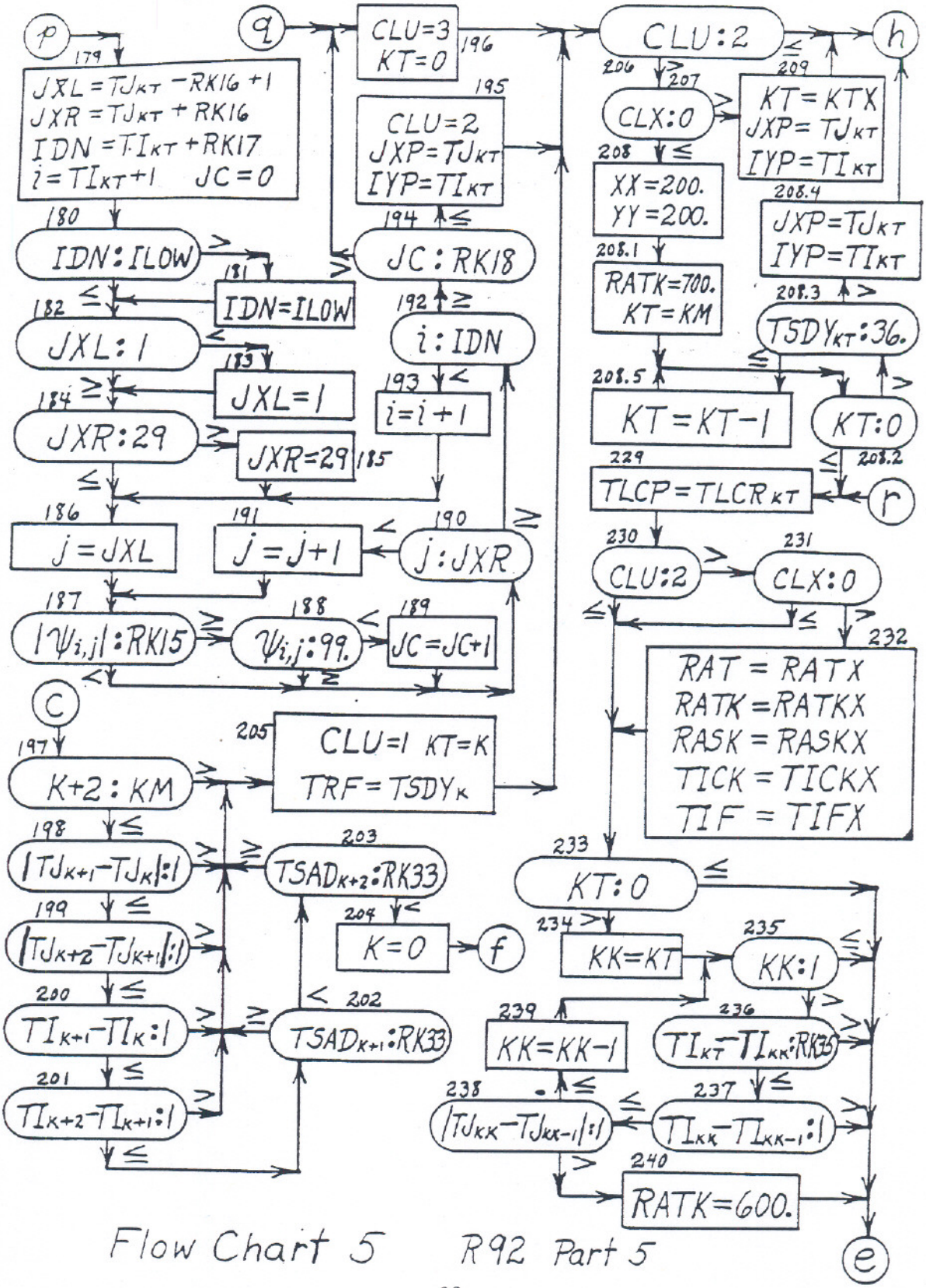
Flow Chart 2
R92 Part 2



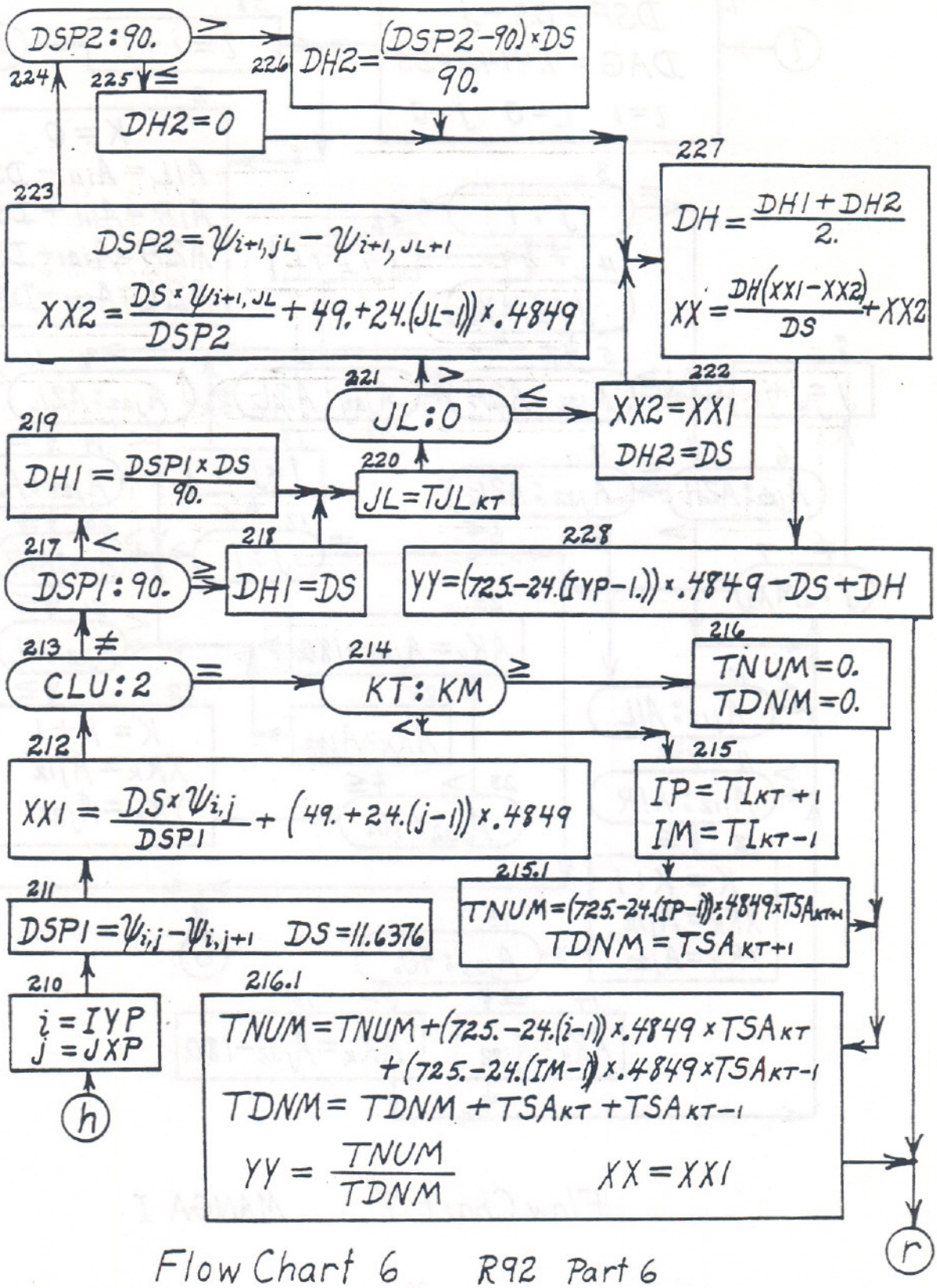
Flow Chart 3 R92 Part 3



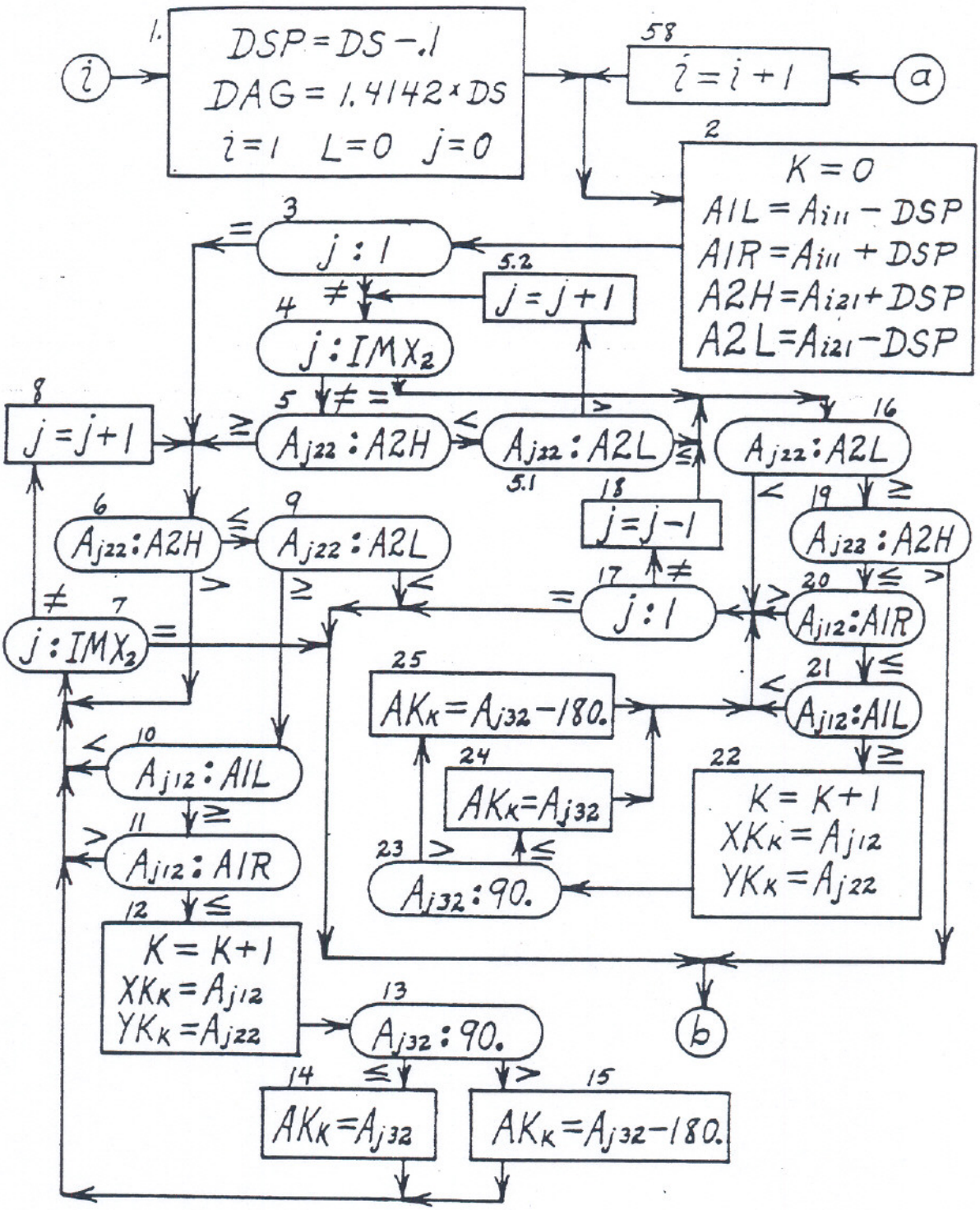
Flow Chart 4 R92 Part 4



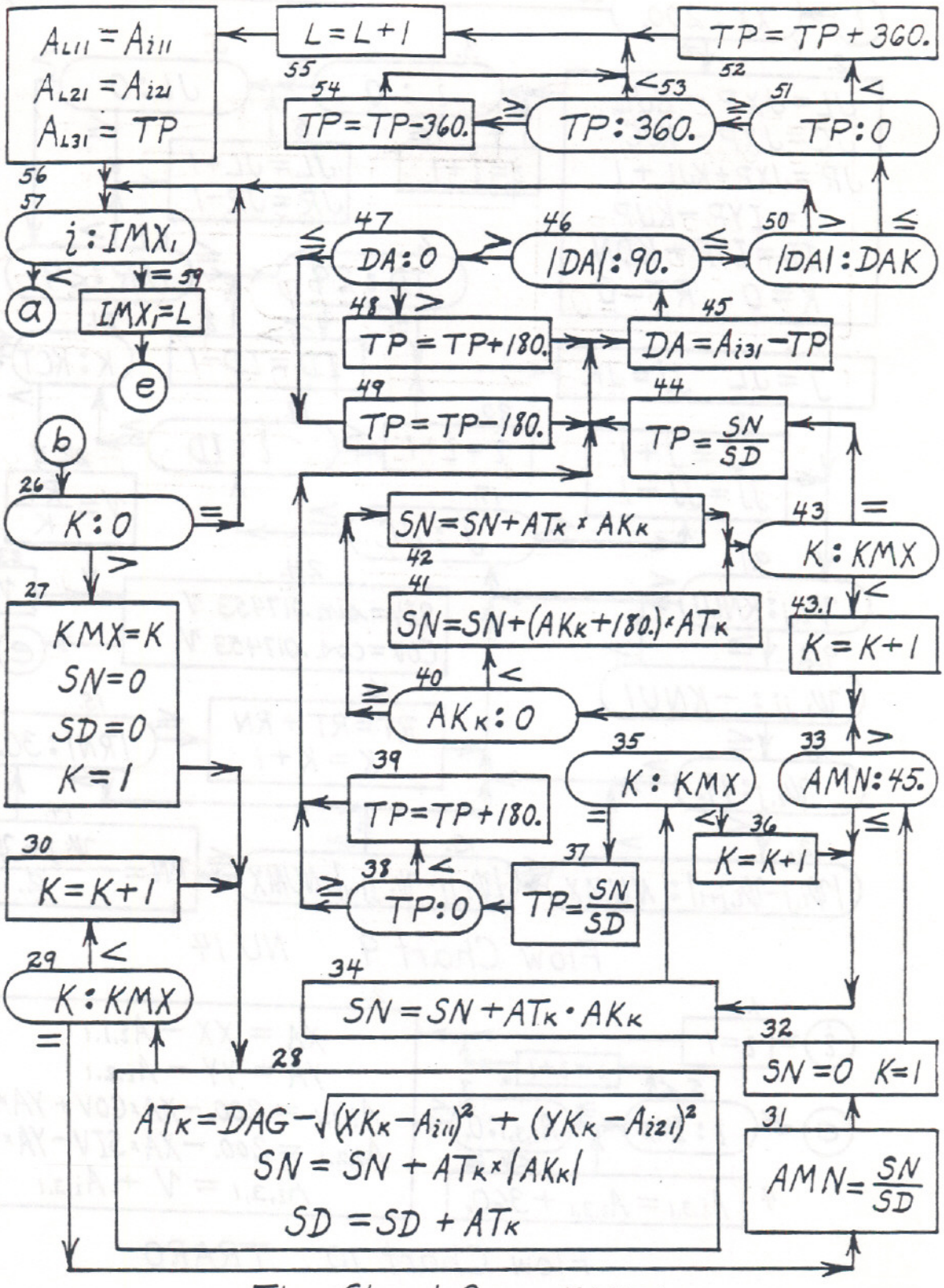
Flow Chart 5 R92 Part 5



Flow Chart 6 R92 Part 6



Flow Chart 7 MANGA I



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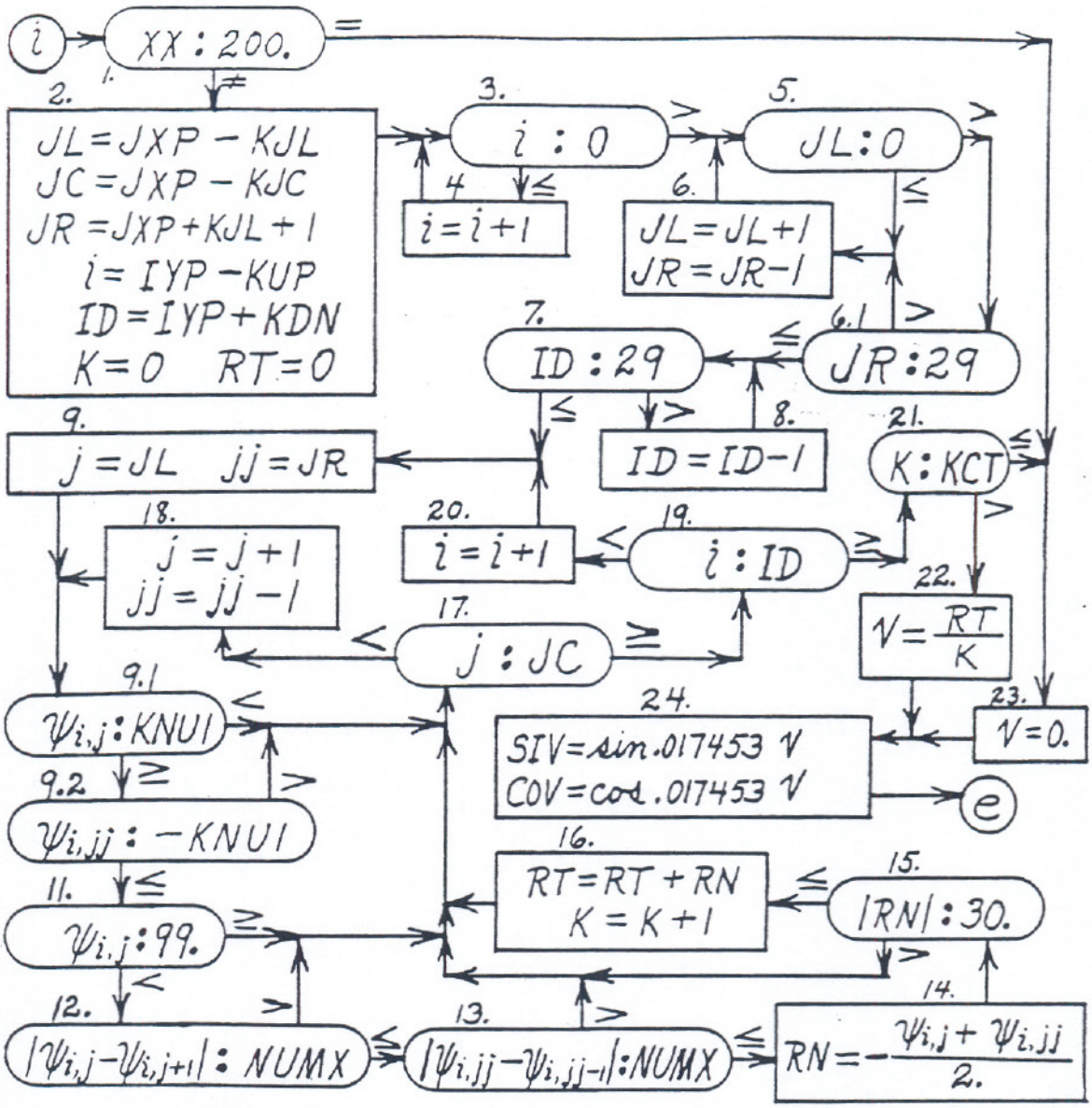
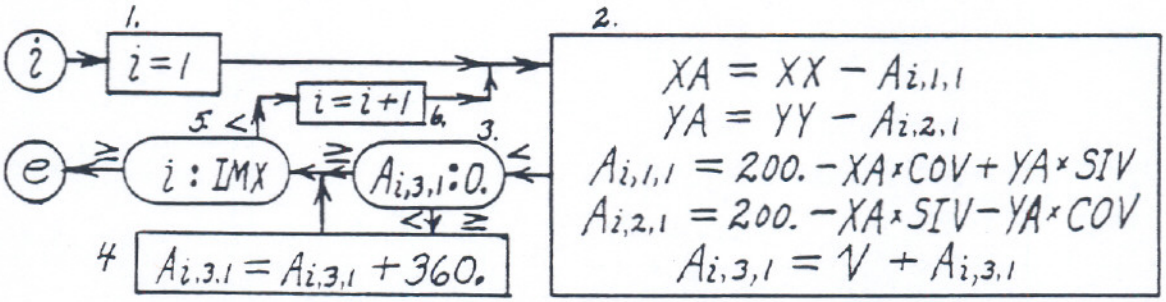


Flow Chart 9 NU 14



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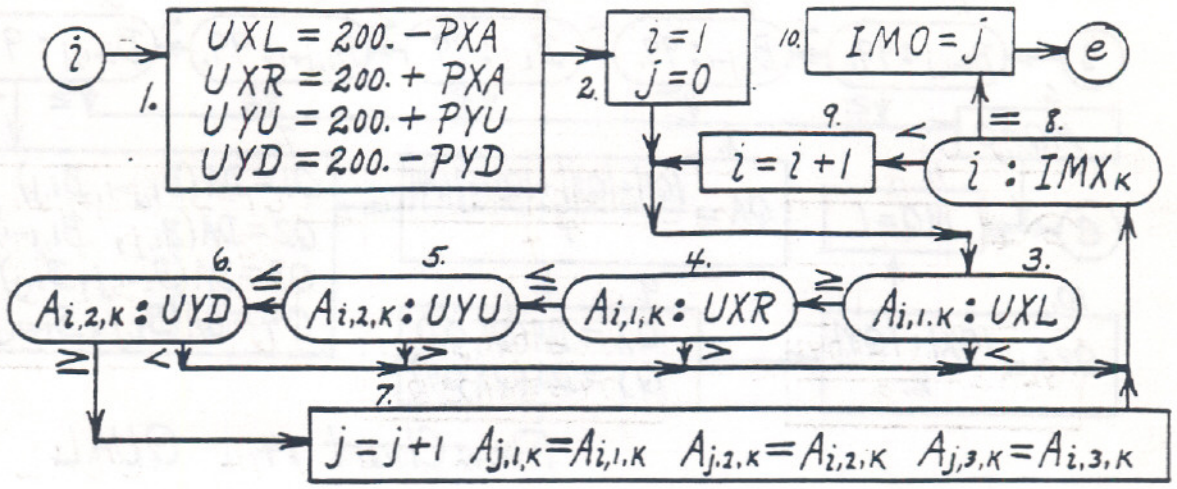

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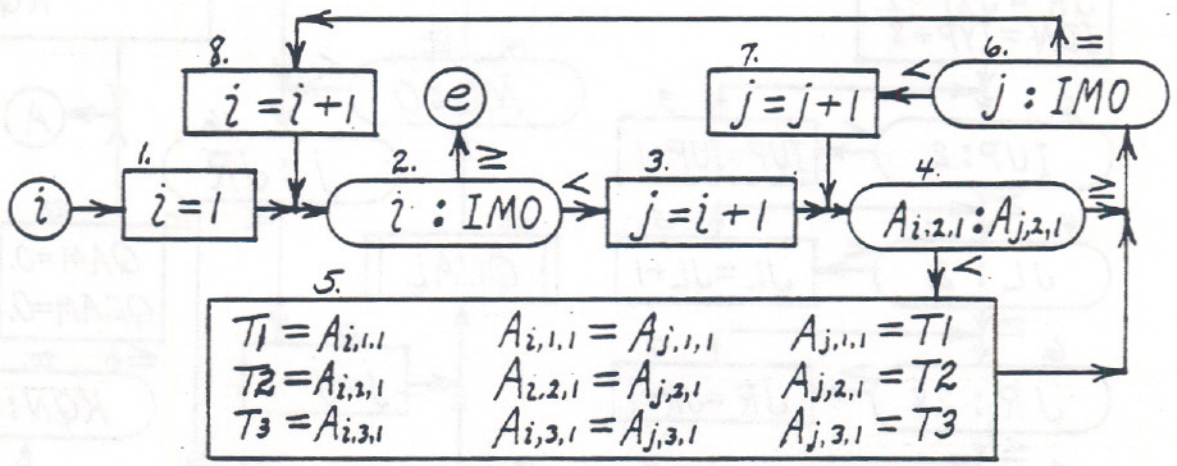
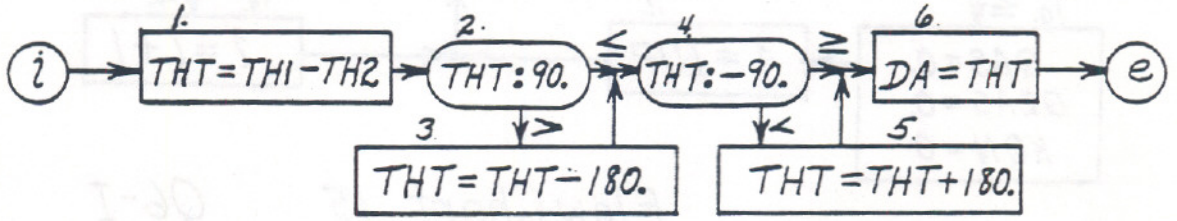
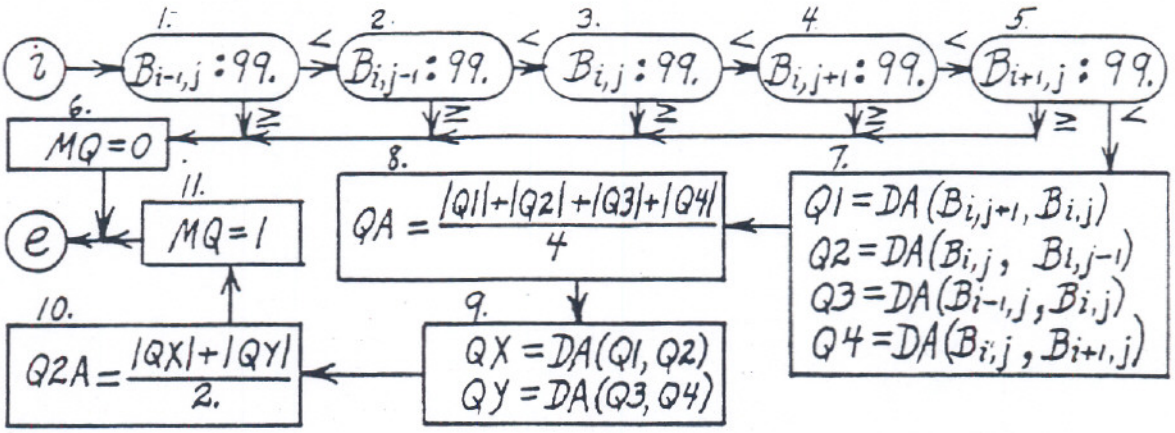


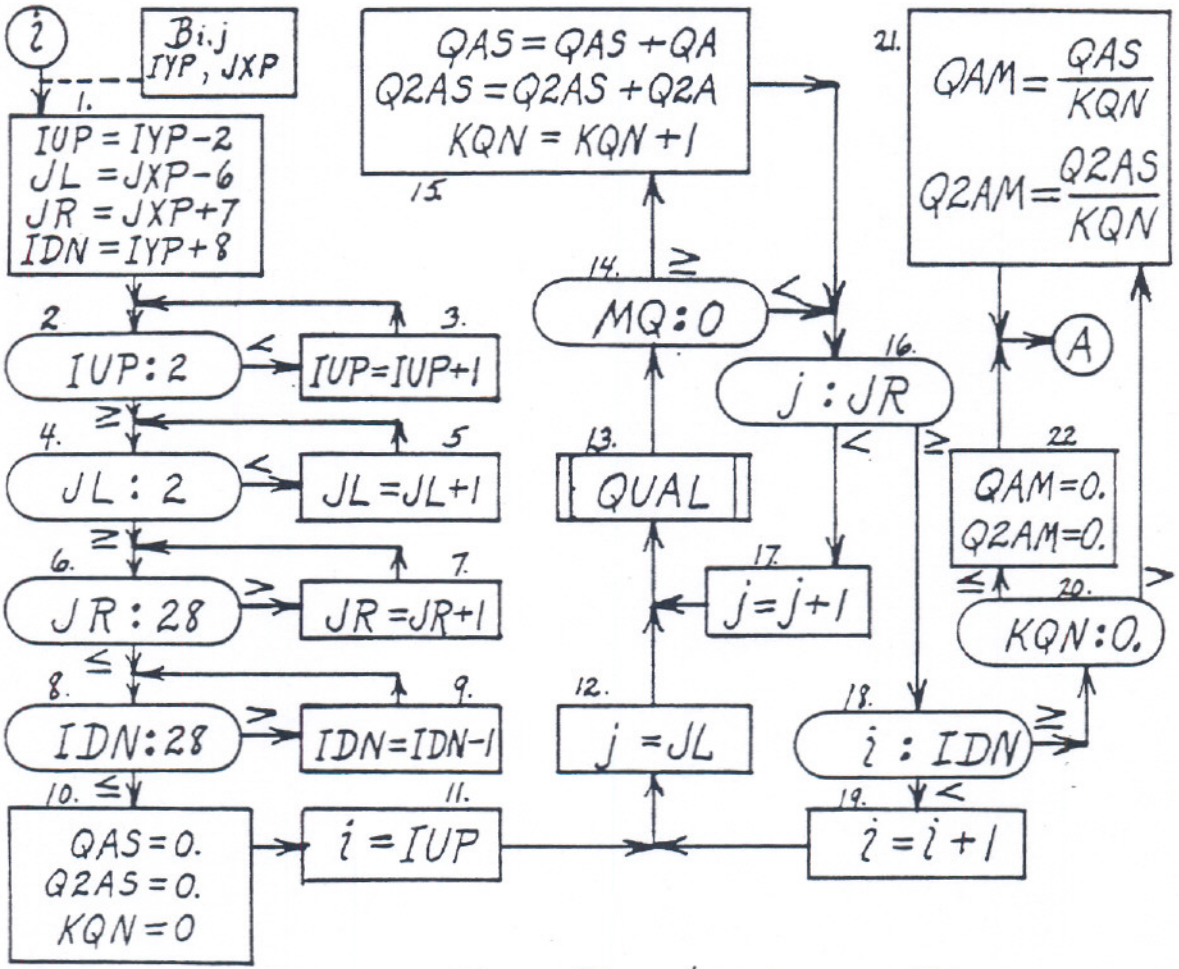
Flow Chart 12 YSORT 2



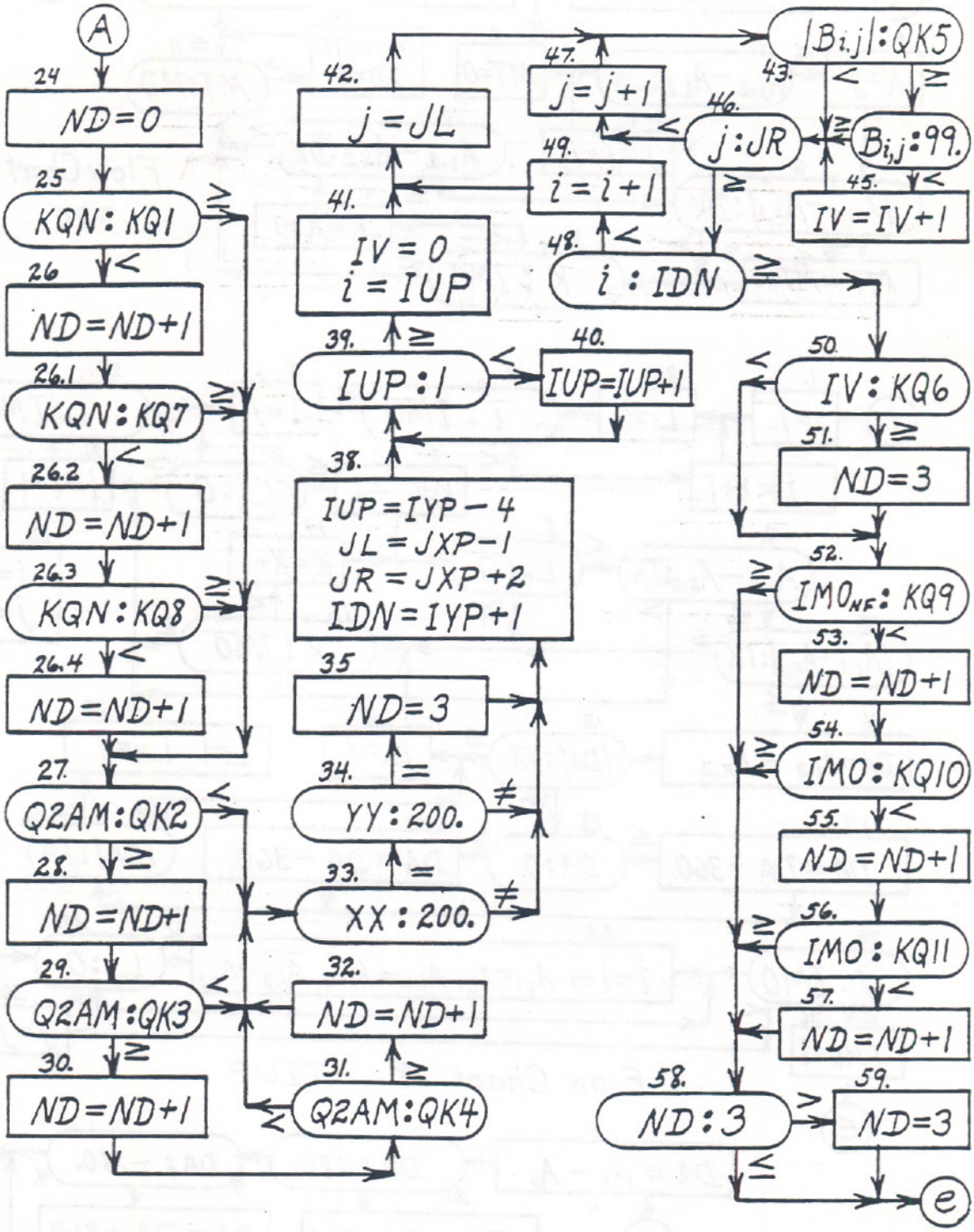
Flow Chart 13 DA (TH1, TH2)



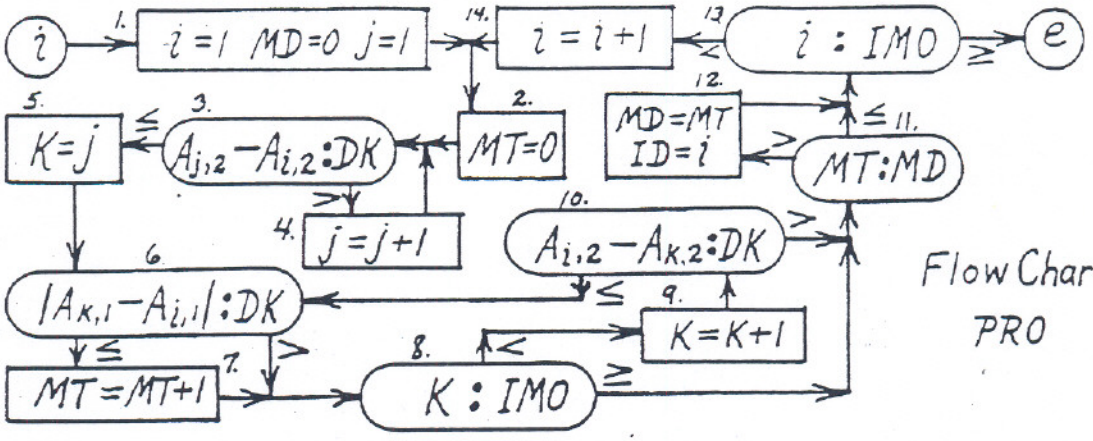
Flow Chart 14 QUAL



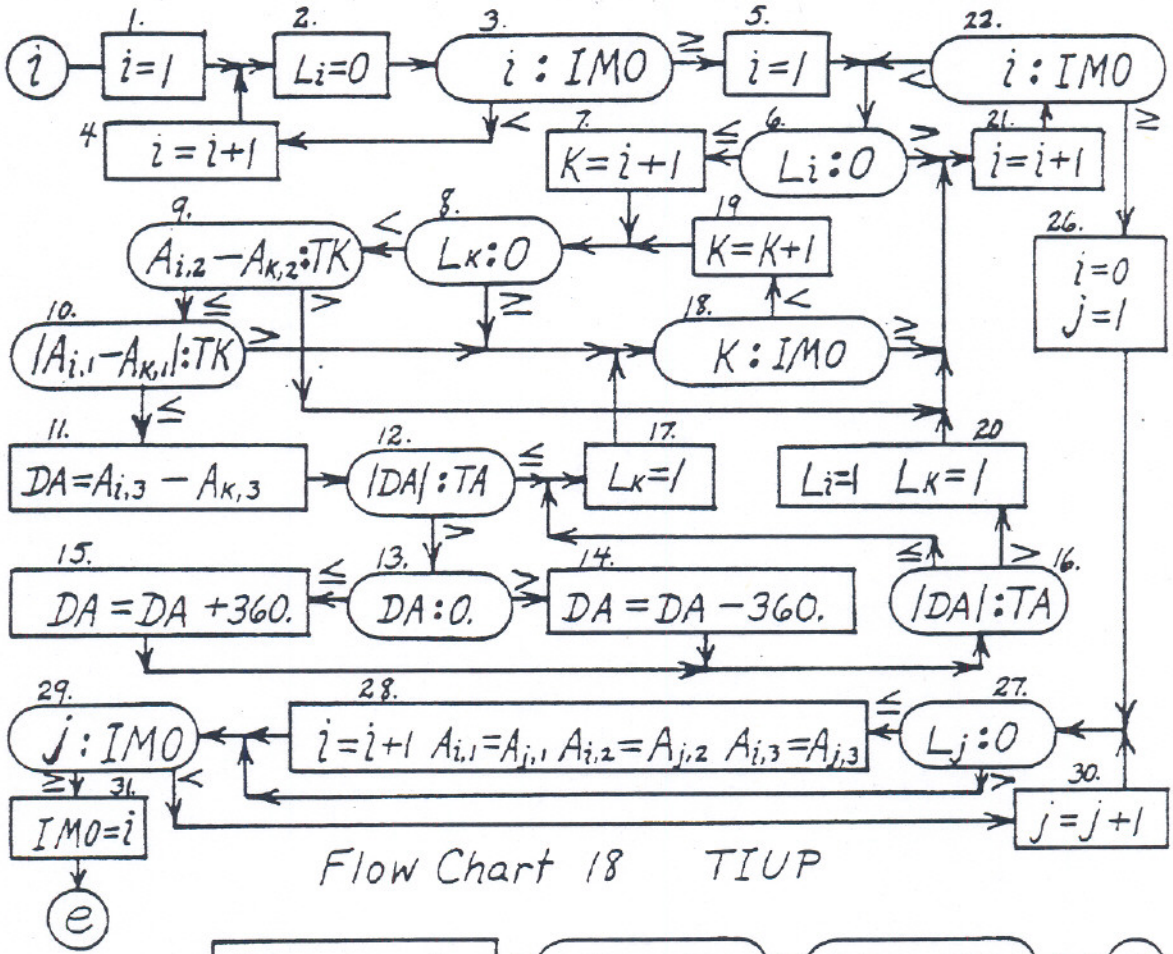
Flow Chart 15 Q6-I



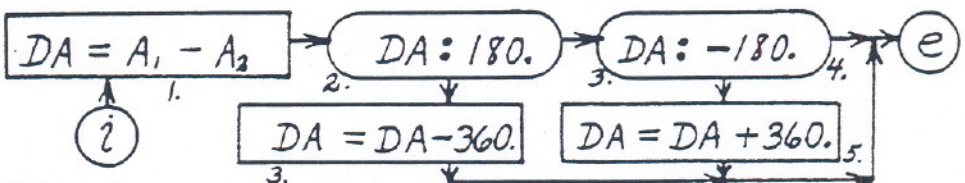
Flow Chart 16 Q6-II



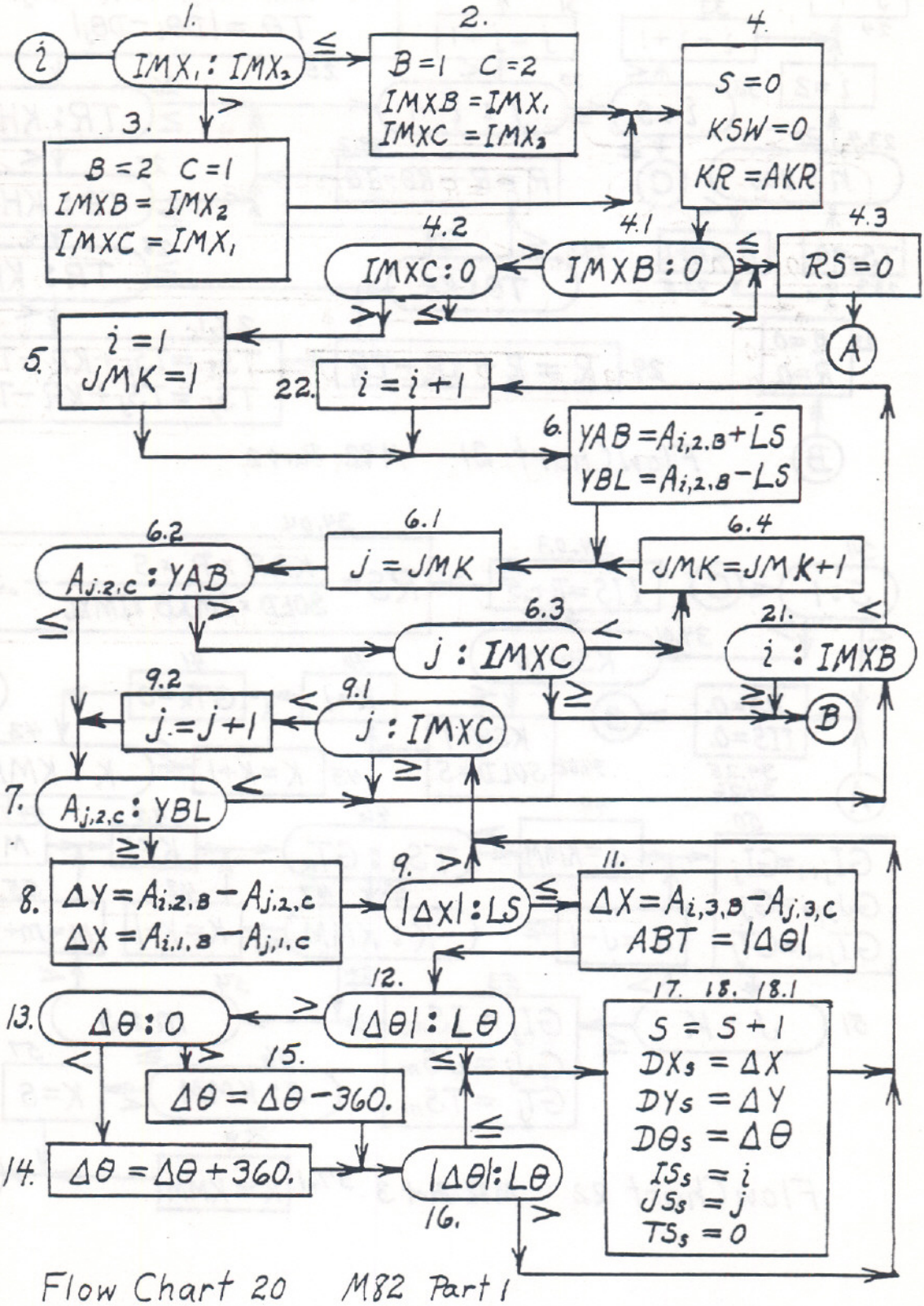
Flow Chart 17 PRO



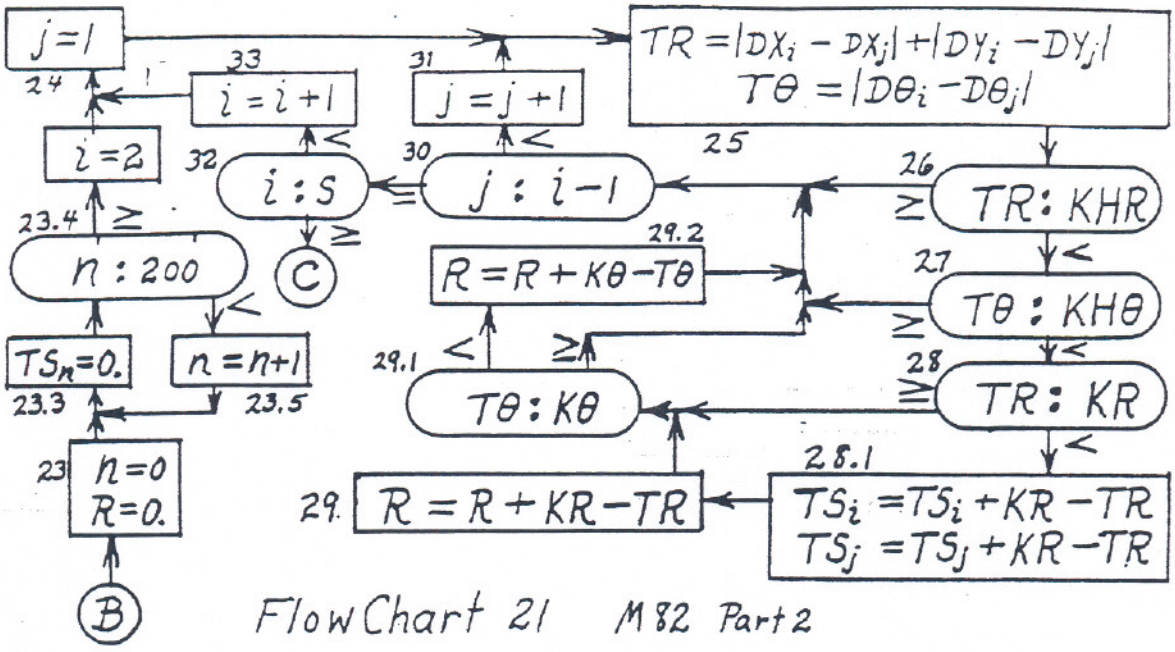
Flow Chart 18 TIUP



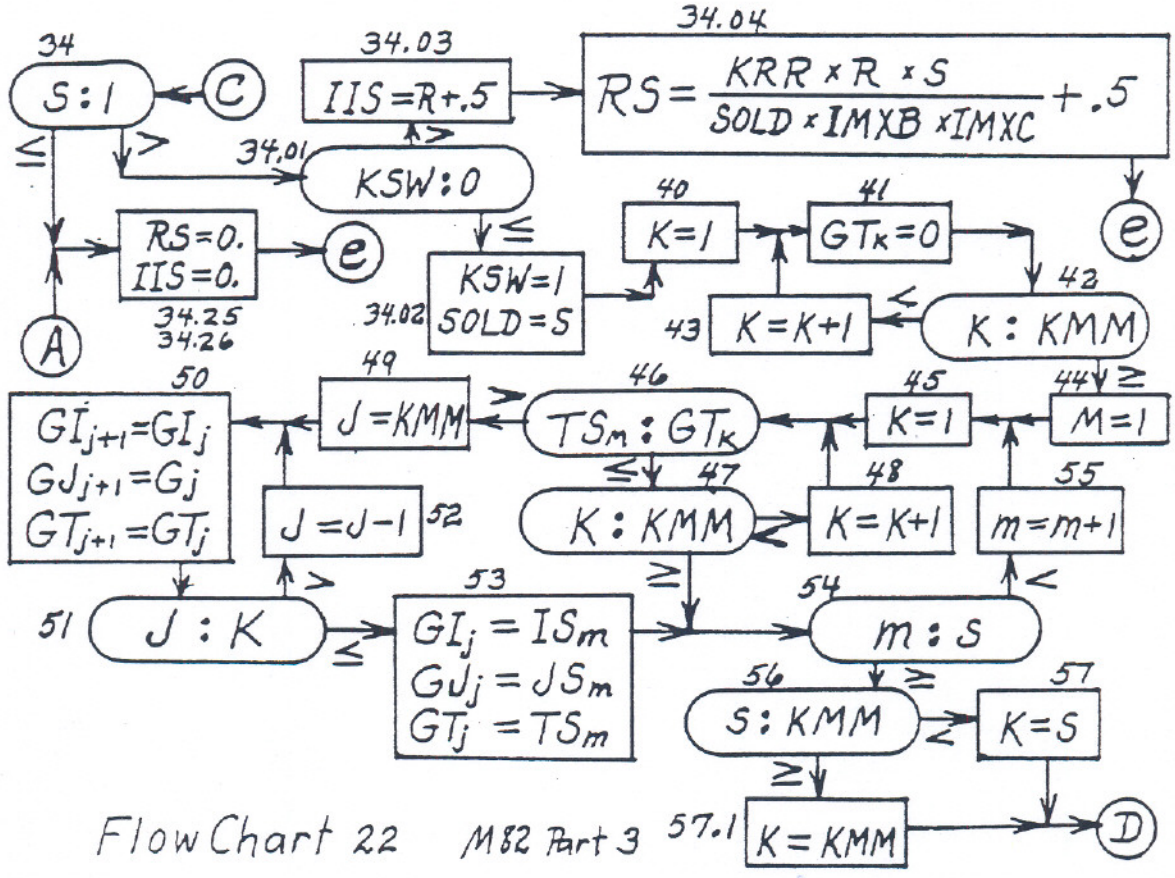
Flow Chart 19 ADA (A1, A2, DA)



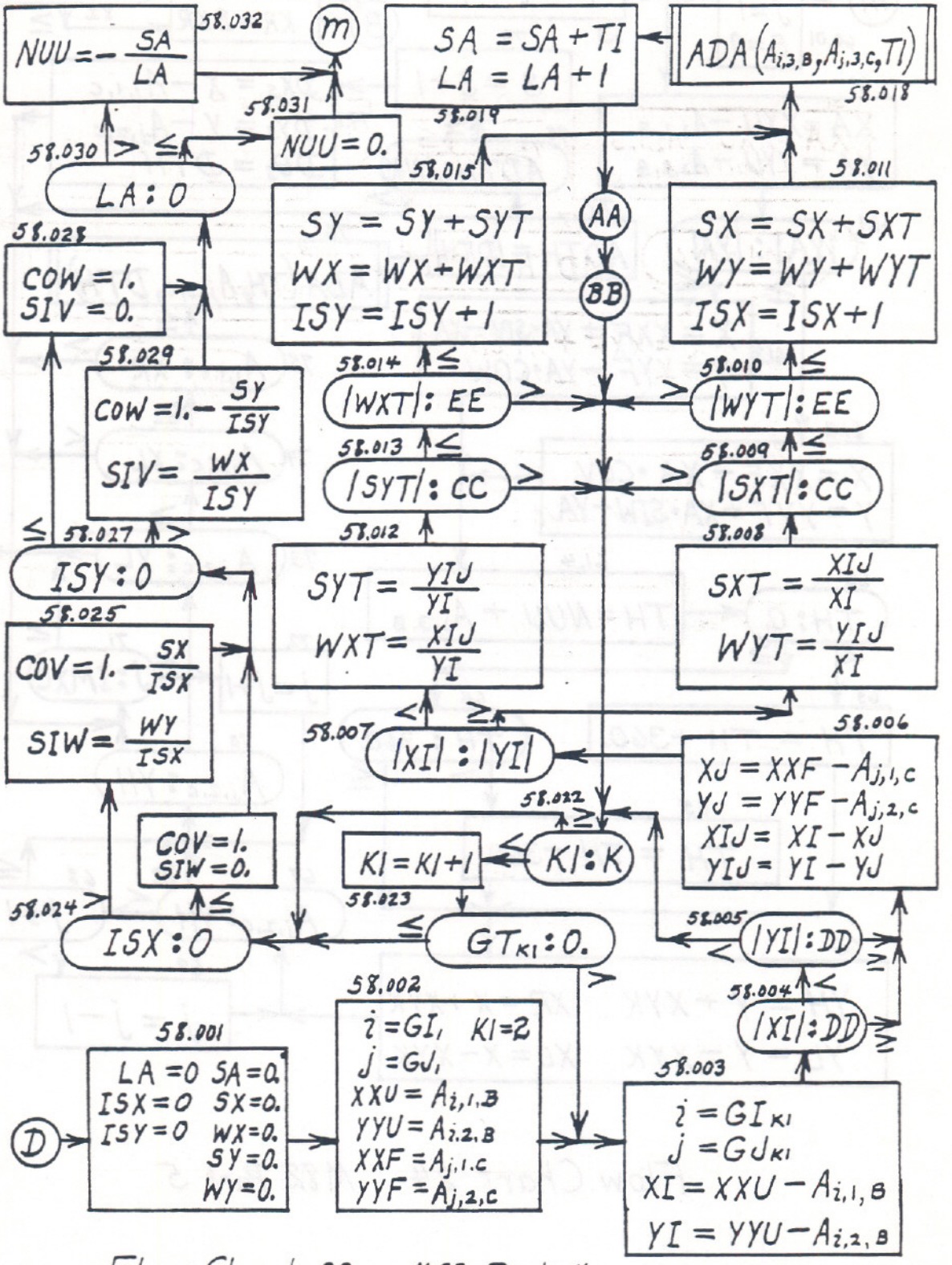
Flow Chart 20 M82 Part 1



FlowChart 21 M82 Part 2



FlowChart 22 M82 Part 3



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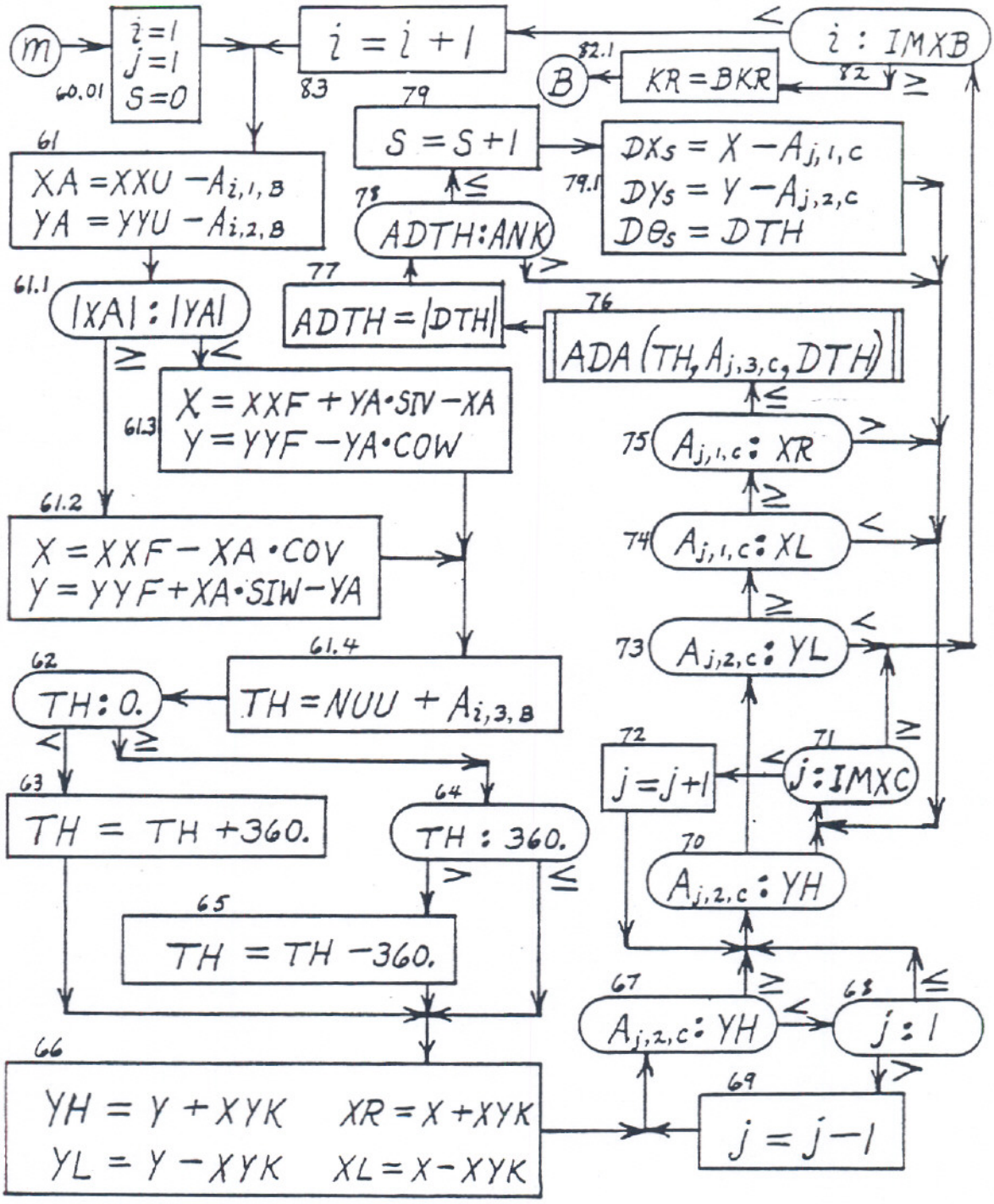

Flow Chart 24 M82 Part 5

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__ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Procedures are described for automatically identifying fingerprints. Machine-read ridge-direction and minutiae data are utilized in registering and enhancing search or file minutiae data. The quality of the data is measured. A procedure is then described for utilizing this minutiae data in determining whether two fingerprint impressions were made by the same finger.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Computerized-fingerprint-identification; identification; pattern recognition.

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